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ACCEPTANCE CRITERIA FOR BITUMINOUS SURFACE COURSE ON CIVIL AIRPORT PAVEMENTS

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16. Abstract

Research was undertaken to extend the use of statistically based airport pavement materials specifications that incorporate price-adjustment features. During the course of the project, data on the physical characteristics of pavement materials were collected from thirteen airport pavement construction projects. A statistical analysis of this data permitted the determination of the parameters (mean and standard deviation) on existing airport construction projects, and these parameters were then used to develop acceptance plans and price-adjustment factors. Operating Characteristics (OC) curves and curves of expected payment were used to determine the appropriate acceptance plans, which were based on the percentage of material falling within specification limits (PWL). By using a continuous rather than a discrete price-adjustment schedule, it was possible to avoid the problem of large differences in payment associated with relatively small differences in quality (as measured by PWL). A computer program was developed to approximate the expected payment curves associated with different continuous price-adjustment systems. This program is applicable to one-sided specification limits such as density. For properties such as air voids, which require both an upper and a lower specification limit, the OC curves were determined by computer simulation of 10,000 randomly drawn samples.

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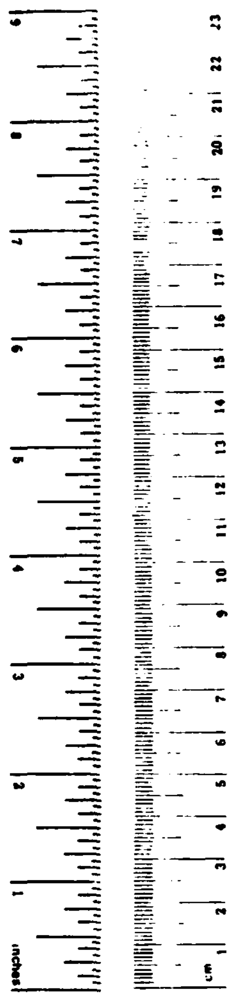
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

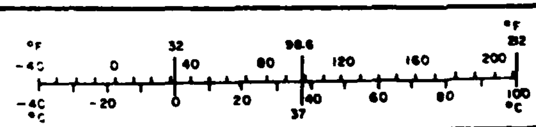
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

In 1978, for the first time, the Federal Aviation Administration (FAA) Eastern Region incorporated statistically based concepts into its bituminous surface course specification (Item P-401). This specification included price adjustment factors for mat density. In order to expand the scope of its statistical specification to include additional acceptance characteristics and price adjustment factors, the FAA contracted with The Pennsylvania State University, through The Pennsylvania Transportation Institute, to investigate the Eastern Region's P-401 specification. This report summarizes the findings of that research.

RESEARCH PROCEDURE

The objective of the research was to make recommendations concerning the development of a statistically based price adjustment acceptance plan for P-401 construction. The research project consisted of three phases. In the first phase, a literature search was conducted to identify the literature on quality assurance that is applicable to the construction of bituminous airport pavements (see Chapter 2). During the second phase of the project, data provided by the FAA Eastern Region were analyzed to determine the population parameters applicable to bituminous airport pavement construction. Information concerning the collection of data is presented in this chapter, while the results of the data analysis are presented in Chapters 3, 4, and 5. In the final phase of the project, the results of the data analysis were used to develop a statistically based acceptance plan, including price adjustment factors, for P-401 material. The development of the acceptance plan is presented in Chapters 3 and 4. The

operation of the proposed acceptance plan was simulated by applying it to the test results of three projects from the study. The results of this simulation are presented in Chapter 6.

DATA COLLECTION

Data for the research were collected by the FAA Eastern Region from thirteen projects in four states during the 1978 construction season. These data were then provided to the researchers. The projects, together with their locations and approximate tonnages, are presented in Table 1.1. As can be seen from the table, a total of over 200,000 tons of bituminous concrete was placed on these projects. Not all of the projects listed in Table 1.1 were governed by the FAA Eastern Region P-401 specification, and this presented some problems in identifying projects on which to simulate the recommended acceptance plan. These problems are discussed in Chapter 6. All samples from the projects were taken in strict accordance with random sampling procedures. Each project in the study was visited by FAA personnel to ensure that the random sampling procedures were understood and were being employed. In spite of these precautions, it was decided that not all of the projects were appropriate for the purposes of the research study, and several were eliminated in determining the population parameters used in the development of the acceptance plans. This factor is addressed later in this chapter.

The data collected from the projects included test results for mat density, joint density, Marshall stability and flow, air voids, asphalt content, and aggregate gradations. Results were available for mat density, Marshall stability and flow, and air voids from all projects. Not all of

TABLE 1.1 PROJECTS FROM WHICH DATA WERE COLLECTED

Project	Location	Tonnage
Adirondack	Saranac Lake, NY	8,210
Butler - Graham	Butler, PA	2,500
Charlottesville - Albemarle	Charlottesville, VA	25,300
Chautauqua County	Jamestown, NY	10,660
Chemung County	Elmira, NY	60,000
DuBois - Jefferson County	DuBois, PA	6,850
Dutchess County	Poughkeepsie, NY	3,250
Linden	Linden, NJ	6,850
Manassas	Manassas, VA	2,230
Blue Ridge	Martinsville, VA	3,050
Richard E. Byrd	Richmond, VA	8,000
Shenandoah Valley	Weyers Cave, VA	33,000
Westchester County	White Plains, NY	36,000
TOTAL		205,900

the projects had results available for the other properties, and only one project had comprehensive results available for joint density.

It should be pointed out that the data resulted from regular daily production and acceptance tests rather than from a designed experiment. This fact presented some problems of analysis. Since there was no designed experiment, it was very difficult to establish reliable correlations among the various measured properties. These difficulties are discussed in Chapter 5. Also, since there were no replicate samples taken and tested, it was not possible to identify the relative amounts of variability associated with sampling, testing, and the production process. For the purpose of this study, all of these components were considered together as the overall variability of the process. While a breakdown of the components of variability would certainly have been informative, the overall variability should be sufficient for the development of the acceptance plan. The use of actual production data in specification development has the advantage of serving as a verification of the industry capabilities under typical construction situations. The data results should, therefore, be helpful in developing acceptance plans which can be met under field conditions.

The researchers had no input into the selection of the projects from which data were to be collected. The researchers did, however, review the procedures for the random sampling of materials presented in the Eastern Region Laboratory Procedures Manual. It was decided that these procedures, if followed on all projects, were sufficient to ensure the unbiased, random sampling necessary for the project. Although it was not possible for the researchers or FAA personnel to be present at all times, it must be assumed that the appropriate sampling procedures were employed on all projects. It is also assumed that all of the projects followed the testing procedures

outlined in the Eastern Region Laboratory Procedures Manual. This is essential to ensure that all of the data which were used were generated from similar testing procedures.

SELECTION OF PROJECTS FOR THE STUDY

The first task was to determine whether all of the projects from which data were collected should be used to develop the acceptance plan. In determining which projects were to be included in the study, it was first decided that on projects which had two separate asphalt plants, each plant would be treated as a separate project. It was judged that asphalt plants on the same project, each having its own job mix formula, were as distinct as asphalt plants on different projects. Three of the projects, Charlottesville, Chemung, and Westchester, each had two asphalt plants. In addition, the Adirondack project had two different job mix formulas (Type A and Type B). It was decided to treat these separately for the purpose of determining parameters for the Marshall properties. This brought the total number of projects available for the study to 17.

After conducting a preliminary analysis on these 17 projects, it was decided to eliminate four from consideration. Two of the projects, Manassas and Martinsville, were governed by specifications which required a 50-blow Marshall test rather than the 75-blow Marshall test required on all the other projects.

The other two projects, Butler and Shenandoah, were eliminated because of the nature of the method employed to develop the specification. The method which FAA had adopted for the development of its acceptance plan is a common approach which calls for the measurement of statistical parameters from acceptable existing construction projects. These parameters can then be used in the development of specifications to ensure that the level of

quality of future projects is at least as high as that on current acceptable projects. The two latter projects were eliminated because their test results were consistently outside of the established specification limits. On the Butler project, the mean value for mat density, 95.6 percent, was more than a full point below the lower specification limit of 96.7 percent. All of the remaining projects had mean values of at least 97.6 percent. In addition, the Marshall test results for the Butler project were consistently outside of the established specification limits. The mean value for air voids was 1.8 percent versus a specification range of 2.7 to 4.7 percent, and Marshall flow values as high as 25 were recorded (the specification limits are 8 to 16). On the Shenandoah project the mean value for Marshall flow was 19.8 versus a specification range of 8-16 and a job mix formula target value of 11; the mean air voids value was 1.6 percent versus a specification range of 2.0 to 4.0 percent and a job mix formula target value of 3.0 percent. While the density results for this project were quite good, it was considered more appropriate to eliminate the project completely than to use selectively the results that were acceptable.

The elimination of these four projects left 13 projects to be used for developing the population parameters appropriate for existing acceptable construction. It should be noted that the 13 "projects" referred to here actually constitute only nine different construction projects: several projects had more than one asphalt plant, as previously discussed. Table 1.2 lists the projects and indicates the types of test results available for each. As can be seen from the table, the results are complete for mat density and Marshall test properties, while nine of the 13 projects had results available for extraction tests. The analysis phase of the project centered on these tests because the greatest amount of data was available for them.

TABLE 1.2 TEST RESULTS WHICH WERE AVAILABLE FOR THE PROJECTS USED IN THE STUDY

Project	Density		Marshall Properties			Extractions		Hot Bin
	Mat	Joint	Stability	Flow	Air Voids	Asphalt Content	Gradation	Gradation
Adirondack - Type A	X		X	X	X	X	X	
Adirondack - Type B	X		X	X	X	X	X	
Charlottesville - ANJ*	X		X	X	X	X	X	X
Charlottesville - SLW	X		X	X	X	X	X	X
Chautauqua	X		X	X	X			
Chemung - Chemung	X		X	X	X			
Chemung - Fisherville	X		X	X	X			
DuBois	X		X	X	X	X	X	X
Dutchess	X		X	X	X	X	X	X
Linden	X		X	X	X	X	X	
Richmond	X		X	X	X	X	X	X
Westchester - Colprovia	X	X	X	X	X	X	X	X
Westchester - Peckham	X	X	X	X	X			

*Drier Drum Plant

2. LITERATURE REVIEW

INTRODUCTION

In the first phase of the project, a review of the literature on quality assurance was conducted. The first goal was to identify work which had been previously performed regarding acceptance plans for pavement materials. The second goal was to identify research on correlations between acceptance characteristics and bituminous pavement serviceability and the cost of production for bituminous pavements.

The primary sources of information were studies which had been performed by various highway agencies throughout the world. The primary sources included in the review were publications of the Transportation Research Board, the Federal Highway Administration, the Association of Asphalt Paving Technologists, the Asphalt Institute, the Transport and Road Research Laboratory (Crowthorne, Great Britain), the Federal Aviation Administration, and various state highway and transportation agencies in the U.S. In addition, a computer search of the TRIS data base was conducted.

ACCEPTANCE PLANS

In reviewing the development of the many statistically based acceptance plans of state highway agencies, it was discovered that there is one major difference from the FAA acceptance plan. In nearly all cases, state highway agencies which were contemplating the use of a statistical specification first conducted designed experiments on designated projects in order to identify the components of variance which were associated with the process. In many cases it was reported that testing variability was greater than

sampling variability, and that testing was a major component in the overall variability of the process (1-4). In the FAA study, the data provided to the researchers were not collected in accordance with a designed experiment, and it is therefore not possible to identify the relative magnitudes of the components of variance. Such an analysis is not crucial to the development of the acceptance plan, since the overall variability of the process can be used, but it is useful in evaluating testing procedures and properties.

TYPES OF PLANS

A number of different acceptance plans were encountered in the literature re[illegible] In some plans, the acceptability of the material is determined from the average, or mean, value of multiple tests conducted on the material. In other plans, the multiple test results are used to determine the percentage of material within specification tolerances (PWT). The latter method is also referred to as the percentage within limits, or PWL, approach.

An acceptance plan that takes into account only the average value of the test results has the disadvantage that it fails to consider the actual variability of the material. Such plans are usually based on an estimated value for standard deviation, which is used for establishing the tolerance limits. It is then assumed that this estimated value remains relatively constant. This assumption may not be valid since it is possible for two lots of material with identical means to have different amounts of variability. This fact would not be identified in an acceptance plan based solely on the mean value of the test results. Such an average value acceptance plan for density is recommended for airfield pavement materials by White and Brown (5).

Several state highway agencies* (6) have developed acceptance plans which consider the variability of the material as well as its mean value. One of these methods is the PWL or PWT method, in which the sample mean and range are used to estimate the percentage of the material which is within specification tolerance limits. Range is used instead of the standard deviation by most states because it is an easier concept to understand. The range is actually used to estimate the standard deviation, and does not provide as good an estimate of PWL as would be provided by the sample standard deviation (9). The density specification employed by the FAA Eastern Region in 1978 was based on the PWL approach using the sample range.

Lot Size

The determination of lot size must be considered in any acceptance plan. In a statistical acceptance plan, material is accepted on a lot-by-lot basis. A lot of material should be produced by essentially the same process. Some definitions of lot are (6):

1. One day's production.
2. The quantity of material represented by a stated number of samples or tests.
3. A specified amount of material.

Each of these definitions has advantages and disadvantages. The use of a day's production as a lot is quite common. Confining the lot to the material produced in one day may help to ensure that all the material in the lot has been produced by the same process. One disadvantage of this approach is that the lot size is highly variable. One thousand tons of material might be produced on one day and only 200 tons on the next. In theory, this varying lot size should not affect the number of samples

*State highway agencies will generally be referred to as states, and in particular, by the name of the state involved.

necessary to estimate the quality of the material, but this may be questioned in a real construction situation.

Defining a lot as a specified amount of material has the advantage of providing uniform lot sizes, but it introduces the disadvantage that the lot may contain material from several construction days. This procedure may make it more difficult to ensure that the material in the lot has been produced by the same process, and it also requires records to be carried over from day to day to determine when the lot has been completed.

Material Properties

A number of different properties were identified as having statistical acceptance plans and price adjustments. The most common of these include asphalt (bitumen) content, aggregate gradation, density, thickness, and smoothness. Of these five, only density is measured for acceptance purposes in the FAA Eastern Region P-401 specification used in 1978. Very few cases were found where price adjustments were applied for the Marshall properties. Louisiana (10) and Mississippi (6) have employed price adjustments for stability. A price adjustment schedule for stability from Louisiana is shown in Table 2.1.

Density was one of the most common properties identified as being accepted on a statistical basis. Density was generally measured by determining the relationship between the in-place density and some target density. The method of determining target density varies from state to state. It was found that 29 states use Marshall specimens to determine the target density (11), and this is also the approach used by FAA. However, 19 states have tried the use of a control strip to establish a target density (11).

TABLE 2.1 PRICE ADJUSTMENT SCHEDULE FOR MARSHALL STABILITY FROM LOUISIANA (10)

Marshall Stability	Percent of Contract Unit Price/Per Lot
1200 and Higher	100
1100 to 1199	95
1000 to 1099	80
Below 1000	50 or Remove

The FAA may want to consider the use of a control strip on projects involving the overlay of existing pavements. This method would take into account the condition of the existing pavement in arriving at the target density. In cases where the existing pavement is badly cracked and provides little support, it may be difficult to achieve an average of 98 percent of the Marshall density in the field. This opinion was expressed to the researchers several times during the conduct of the project. It should be noted, however, that there are some potential disadvantages associated with the use of a control strip. Major modification to the existing specifications would be required since they were not developed for this approach. The current specification was developed to assure that the in-place air voids remain below 7 percent and that a minimum 1000 pounds in-place stability be obtained. It is not clear how these objectives would be assured under the control-strip approach. Another potential disadvantage to the control-strip approach is that it may provide the contractor with an incentive to reduce his compaction effort on the control strip to make it easier for him to meet the resulting compaction requirements.

The use of thickness for acceptance purposes is another point which should be considered by FAA. Currently, thickness measurements are not required by the FAA Eastern Region P-401 specification. Pavement thicknesses below the design value can lead to reduced pavement life. Thickness would be particularly easy to measure on projects which are already using cores for density determination. The same cores could be used for both thickness and density measurements.

CORRELATIONS

The second objective of the literature review was to locate correlations that might have been identified between acceptace characteristics and pavement serviceability and the cost of production for bituminous pavements. The literature review, although extensive, failed to identify any direct correlations between acceptance properties and pavement serviceability for the properties which are measured by FAA. The purpose of such correlations would be to develop a rational price adjustment system which would relate deficiencies in acceptance properties with their corresponding effect on pavement life or performance.

In some cases where attempts have been made to relate acceptance properties to their effect on pavement life, properties included in the design procedure for the pavement are used, for example, pavement thickness and flexural strength. These values can be determined and then substituted into design equations, curves, or nomographs to determine the associated reduction in pavement life. This reduction in life can be compared with the design life of the pavement, and price reductions can be calculated accordingly. This approach has been employed in New Jersey (7, 12) for the development of price adjustment schedules. This approach might be developed for thickness for both flexible and rigid pavements and for flexural strength for rigid pavements by using the FAA design curves. Other attempts have been made to correlate asphalt content (7, 13) and smoothness (7) to pavement performance. All of these cases deal with properties that are not currently used for acceptance purposes in the FAA Eastern Region P-401 specification.

Some indirect correlations have been identified for asphalt content and total voids content. The correlations actually relate these properties with their effects on the fatigue life of asphaltic concrete. It has been

noted by Pell (14) and Chow (15) that bitumen content and voids content are among the most important factors affecting fatigue performance. It is not clear, however, that the reduction in fatigue life associated with increased voids content can be directly related to price adjustments for air voids content as determined from Marshall test specimens.

It has been suggested by Van de Fliert and Schram (16) that the results of fatigue tests on asphalt concrete can be used to estimate reductions in pavement service life. They indicate that excessive voids caused by insufficient compaction result in a reduction in pavement life of 25 percent for each percentage increase in voids, and that this is a cautious estimate. For the case of bitumen content, they indicate that "for every reduction of 0.3 percent in bitumen content, service life is reduced on average by a factor of 0.75, provided that the bitumen content does not fall to very low values."

3. DENSITY

INTRODUCTION

This chapter presents the findings of the data analysis for mat density. Since only one construction project had data for joint density, it was judged that there were not sufficient data available to develop population parameters or an acceptance plan for joint density. The findings from the mat density analysis are compared with the values assumed by FAA in the development of the density specification used in 1978. The acceptance plan from this specification is reviewed, and the development of the acceptance plan proposed by the researchers is presented.

ANALYSIS OF DENSITY TEST RESULTS

The density test results from each of the projects in the study were analyzed, and the mean and standard deviation were determined for each project. The results of this analysis are presented in Table 3.1. As can be seen from the table, there were a total of 733 density determinations on the projects studied. The pooled mean and standard deviation for these density values are 98.45 percent and 1.19 percent, respectively.

The values for population mean and standard deviation shown in Table 3.1 can be compared with the values which were assumed by FAA Eastern Region in the development of their density specification for the 1978 construction season. The FAA values were a mean of 98 percent and a standard deviation of 1.3. These compare quite well with the values of 98.45 and 1.19 obtained from the density data. It appears that the construction projects studied achieved values that were superior to those assumed by FAA.

TABLE 3.1 RESULTS OF MAT DENSITY TESTS FOR PROJECTS IN THE STUDY

Project	Number of Tests	Mean	Standard Deviation
Adirondack	60	98.83	1.14
Charlottesville - ANJ	80	97.58	2.14
Charlottesville - SLW	73	97.74	1.67
Chautauqua	45	99.35	0.71
Chemung - Chemung	38	98.76	0.77
Chemung - Fisherville	80	99.23	0.92
DuBois	40	98.61	1.01
Dutchess	12	97.57	0.73
Linden*	77	98.53	0.45
Richmond	36	97.96	0.83
Westchester - Colprovia*	110	98.55	0.94
Westchester - Peckham*	82	98.36	1.05
TOTALS	733	98.45	1.19

*On these projects, density for acceptance purposes was determined by nuclear density device.

FAA DENSITY ACCEPTANCE PLAN

A brief review of the density acceptance plan used during the 1978 construction season (from this point referred to as the FAA plan) may be useful.

Specification Limits

The FAA acceptance plan allows acceptance to be based on density values obtained from either cores or nuclear devices. Acceptance was on a lot-by-lot basis, with a lot defined as one day's production. When cores were used for acceptance, four samples per lot were taken, whereas when nuclear density devices were used, the number of tests per lot was seven. The extra tests were made possible by the greater speed and ease associated with the use of nuclear density devices. The lower specification limit in the FAA acceptance plan was set at 96.7 percent when cores were used, and 97.0 percent when nuclear devices were used. The method of acceptance of material was based on the percentage of material that was above the specification limit, as estimated from the test results for the lot.

Comments on Specification Limits

By requiring a minimum of 90 percent within limits for full payment for nuclear devices, with a specification limit of 97.0, and a minimum of 90 percent within limits for full payment for cores, with a specification limit of only 96.7, a higher quality is actually being specified for the case when nuclear devices are used. Both of these specification limits require material of higher quality than the values of mean (98) and standard deviation (1.3) which were assumed by FAA. This is illustrated in Figure 3.1.

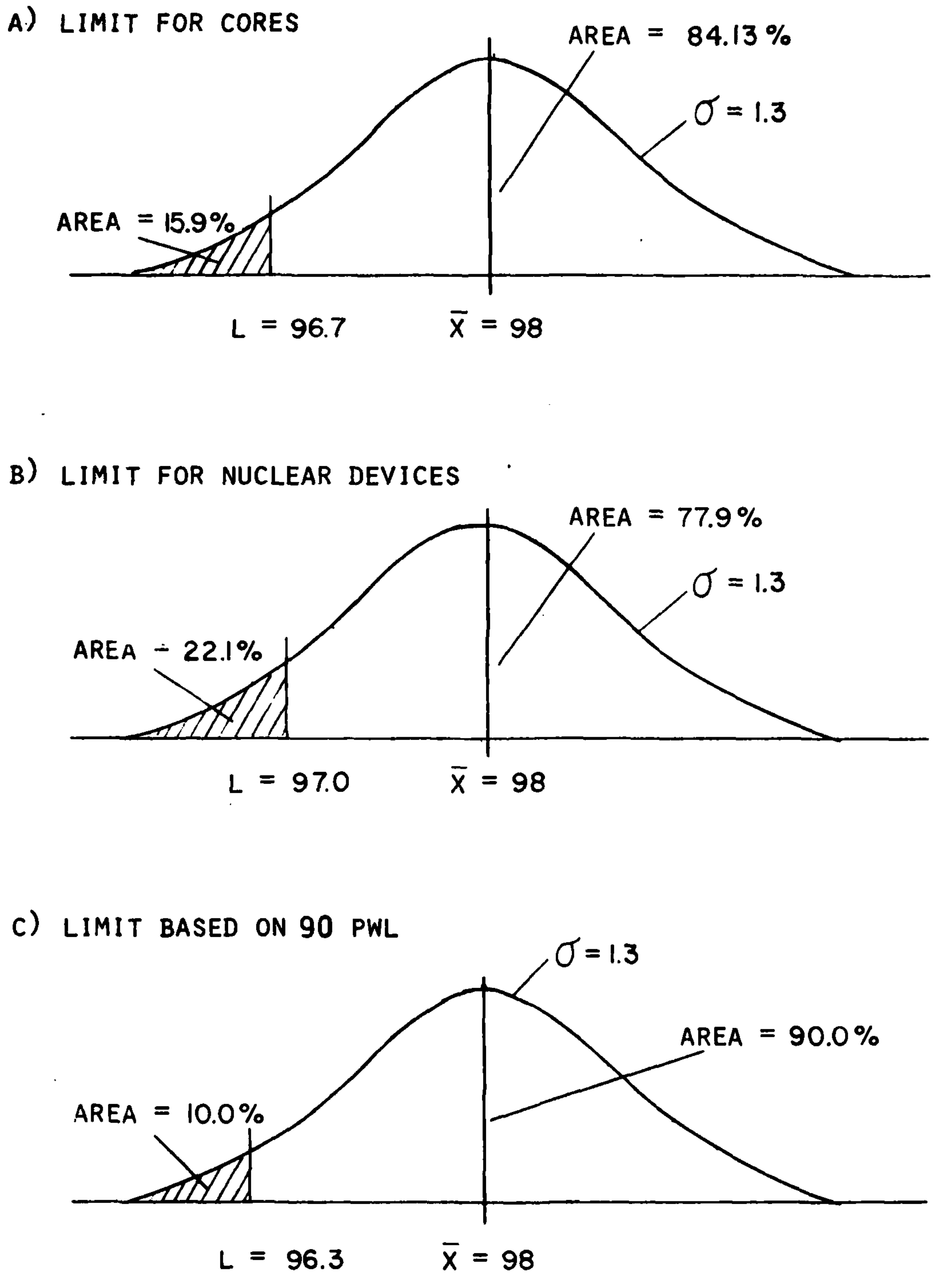


FIGURE 3.1 COMPARISON OF LOWER DENSITY SPECIFICATION LIMITS FOR MEAN AND STANDARD DEVIATION VALUES ASSUMED BY FAA

Figure 3.1 illustrates the case of a contractor who is producing material which is exactly comparable to that assumed by FAA, i.e. a mean of 98 and standard deviation of 1.3. For this contractor, the percentage of material that would be above the core lower limit of 96.7 is 84.1 percent, as indicated in Figure 3.1a. If this same material were produced under the nuclear density device specification limit, only 77.9 percent of the material would be above the limit of 97.0 percent, as indicated in Figure 3.1b. The FAA acceptance plan requires that 90 percent of the material be above specification limits for full payment. Figure 3.1c indicates that for a contractor producing material at a mean of 98 with a standard deviation of 1.3, 90 percent of the material would fall above a value of 96.3. This seems to indicate that the lower specification limit for density should be set at 96.3 percent to be consistent with the original FAA assumptions. The topic of a lower specification limit for density will be discussed further when the proposed new acceptance plan is presented.

Price Adjustments

The price adjustment schedule from the FAA plan is presented in Table 3.2. It can be seen that at least 90 percent of the material must be within the specification limits (referred to as 90 percent within limits or PWL) for the material to be accepted at full payment. For material that is less than 90 PWL, the material is accepted but at a reduced payment. The incremental payment reductions increase as the level of quality, as measured by PWL, decreases. Since the price reductions become more severe as the quality of the material decreases, the contractor is encouraged to produce acceptable material, rather than to produce inferior material at a reduced price.

TABLE 3.2 PRICE ADJUSTMENT SCHEDULE FROM FAA DENSITY ACCEPTANCE PLAN

Percent Above Lower Tolerance Limit	Percent of Contract Price to be Paid
90-100	100
85-89	98
80-84	95
75-79	90
70-74	80
65-69	70
Less than 65	*

*The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu thereof, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall not be removed and will be paid for at 50 percent of the contract unit price.

The Operating Characteristics (OC) curves for the FAA plan, shown in Figure 3.2, were developed by numerical integration techniques, described later in this chapter. The OC curves graphically represent the relationship between the actual quality of a lot and its probability of acceptance. For the FAA plan, a set of OC curves is required in order to show the probability of a lot being accepted at any of the possible payment levels. The curves shown in Figure 3.2 are for a sample size of four, as is the case for acceptance by cores in the FAA Eastern Region specifications.

OC curves presented in terms of actual PWL versus the probability of acceptance (Figure 3.2) are independent of the specification limit. For example, when a contractor produces material with a given mean and standard deviation, the actual PWL value can be determined from tables of the area under normal distribution. If a contractor produces material with a mean value of 98 percent and a standard deviation of 1.0 percent and the specification limit is 96.7 percent, then the actual PWL value can be determined to be 90.3 percent. If the specification limit is changed to 97.0 percent and the contractor's mean and standard deviation do not change, then the actual PWL of the material will be 84.1 percent. Figure 3.2 can be used to determine the probability of acceptance at any payment level (100%, 98%, 95%, etc.) for each of these cases. The figure can be used for any specification limit, the only difference being that the actual PWL value of the material will be different for each specification limit.

Another useful relationship for examining the reasonableness of an acceptance plan is quality of the material, as measured by PWL, versus expected payment. This relationship is plotted in Figure 3.3 for the FAA plan. Expected payment can be thought of as the average payment over the long run. The development of the expected payment curve shown in Figure 3.3 is illustrated in Table 3.3. To arrive at the curve shown in Figure 3.3, it

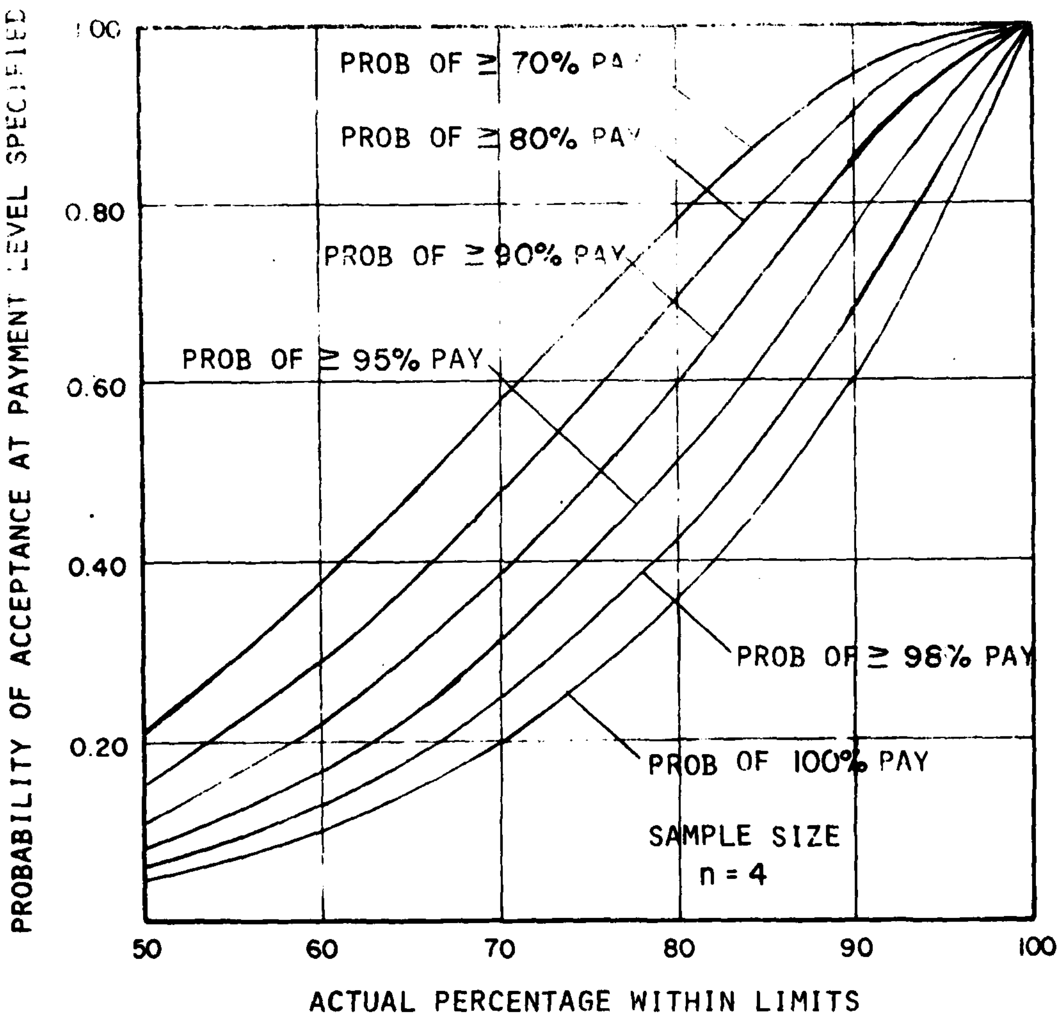


FIGURE 3.2 SET OF OPERATING CHARACTERISTICS CURVES FOR THE FAA DENSITY ACCEPTANCE PLAN

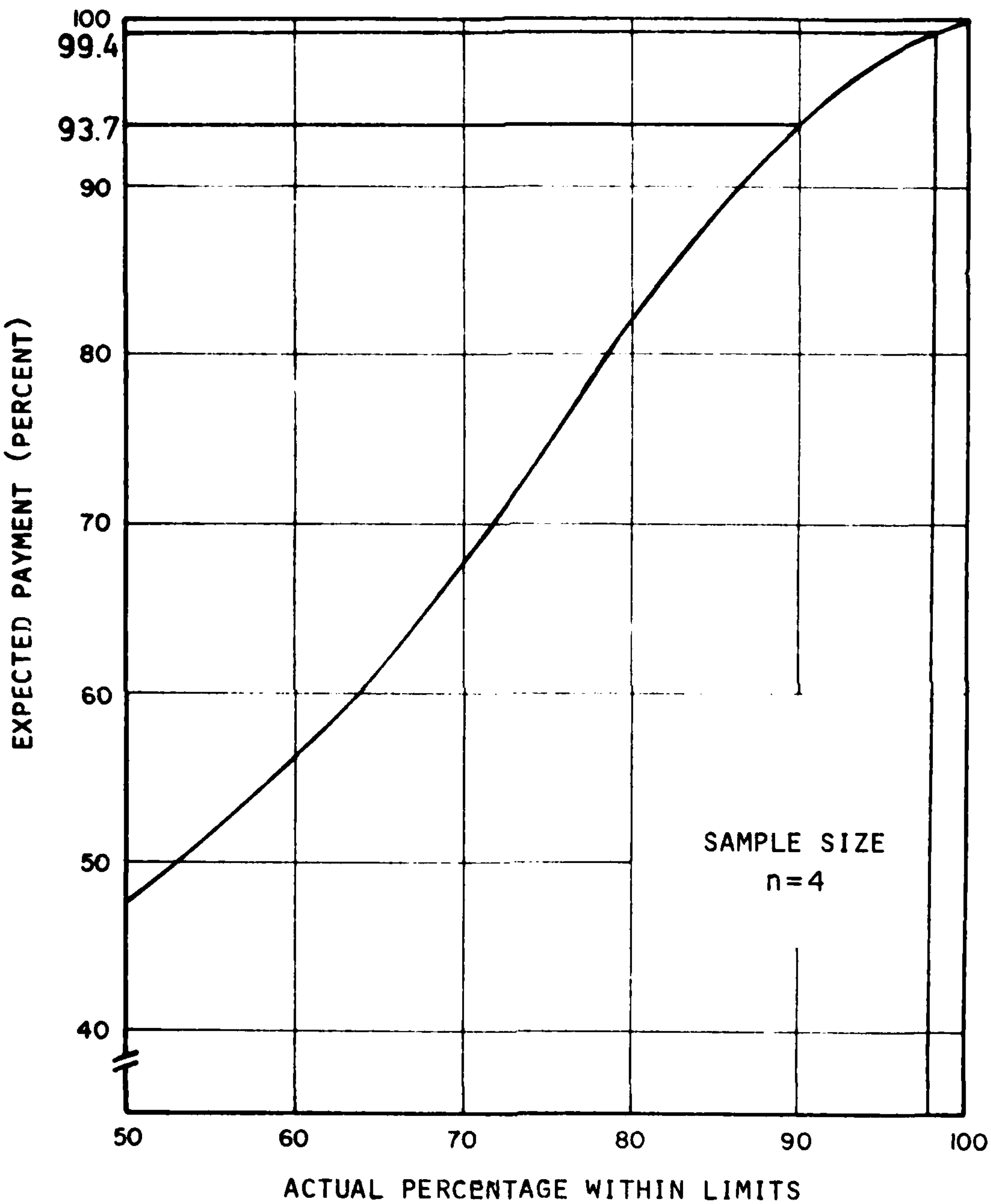


FIGURE 3.3 EXPECTED PAYMENT CURVE FOR THE FAA DENSITY ACCEPTANCE PLAN

TABLE 3.3 EXPECTED PAYMENT CALCULATIONS FOR FAA DENSITY ACCEPTANCE PLAN

Actual PWL	Probability of Receiving Indicated Payment								Expected Payment Σ (Payment) x (Probability of Receiving Payment)
	100	98	95	90	80	70	50*	0	
50	.0479	.0154	.0215	.0305	.0428	.0591	.5871	.1957	48.0
60	.1032	.0298	.0399	.0531	.0690	.0864	.46395	.15465	[illegible]
70	.1997	.0500	.0631	.0776	.0915	.1013	.3126	.1042	67.9
80	.3584	.0724	.0836	.0921	.0948	.0890	.18873	.02097	82.[illegible]
90	.6110	.0814	.0805	.0732	.0599	.0427	.0513	0	[illegible]
98	.9136	.0367	.0249	.0143	.0068	.0026	.0011	0	99.[illegible]

*The following assumptions were made for the case when the estimated PWL is less than 6[illegible] and the material can either be removed and replaced or accepted at 50 percent payment:

1. If 50 < actual PWL < 80, accept at 50% pay 75% of the time
2. If actual PWL = 80, accept at 50% pay 90% of the time
3. If actual PWL > 80, accept at 50% pay 100% of the time.

is necessary to make certain assumptions concerning the probability of receiving 50 percent payment when the material has an estimated PWL less than 65. As shown in Table 3.2, when the material has less than 65 PWL, it can either be removed and replaced or it can be accepted as is at a payment level of 50 percent. In arriving at the expected payment curve, the following assumptions were made in the case when the estimated PWL is below 65:

1) When the actual PWL is between 50 and 80, the material is accepted at 50 percent payment 75 percent of the time.
2) When the actual PWL is equal to 80, the material is accepted at 50 percent payment 90 percent of the time.
3) When the actual PWL is above 80, the material is accepted at 50 percent payment 100 percent of the time.

These assumptions were made by the FAA Eastern Region in its Engineering Bulletin No. 8 and have been used by the researchers because they appeared to be reasonable. It seems likely that in nearly all cases the option of acceptance at 50 percent payment will be chosen since it is the easiest course of action.

The expected payment curve in Figure 3.3 requires the specifying agency's subjective judgment on the reasonableness of the curve. Since this curve is based on the price-adjustment schedule developed by FAA, that agency undoubtedly considered it acceptable. The curve in Figure 3.3 seems reasonable. If a contractor produces material which is actually 98 percent within limits, then his expected payment is nearly 100 percent (99.4 from Table 3.3). For a contractor producing material which is 90 percent within limits, the expected payment is 93.7 percent. If the correct decision were made every time, that is, if the PWL value of 90

percent were known with certainty, then this contractor would receive 100 percent payment at all times. Since the PWL value must be estimated from sample results, there will be some risk that material from a particular lot which is actually 90 PWL will receive a reduced payment. This risk is indicated by the expected payment value of 93.7 percent associated with an actual PWL of 90 percent, shown in Figure 3.3. On the other hand, there is also a chance that a particular lot of material will receive a higher payment than would be made if the PWL value were known with certainty. For example, if the contractor produces material which is actually 60 PWL and the correct decision is made every time, then his expected payment should be no more than 50 percent (see Table 3.2). However, the expected payment for an actual PWL value of 60 from Figure 3.3 (or Table 3.3) is 56.6 percent. Therefore, even though a subjective analysis must ultimately be made by the FAA, the risks in this plan appear to be equitably shared by the contractor and the owner.

DEVELOPMENT OF PROPOSED ACCEPTANCE PLAN

In light of the fact that no direct correlations were identified between the FAA acceptance characteristics and pavement serviceability, it was decided to base the development of acceptance plans and price adjustments on the reasonableness of their Operating Characteristics (OC) curves and curves of Expected Payment. This approach is one of four described by Willenbrock and Kopac (17). Since this approach requires some subjective decisions concerning the reasonableness of the acceptance plan and price adjustments, the starting point which was used in the development of the proposed acceptance plan was the density plan employed by the FAA Eastern

Region. Before the acceptance plan and price adjustment factors were considered, the problem of the specification limit for density had to be resolved.

Development of Specification Lower Level

In order to arrive at a new acceptance limit, the pooled estimates for population mean (98.4) and standard deviation (1.2) for density were used. The population with these parameters was compared with one having the parameters originally assumed by FAA. As a compromise, a third population was considered, which had the FAA mean target density of 98 percent and used the pooled estimate for standard deviation of 1.19 percent. These three cases are presented in Figure 3.4. Since a minimum of 90 PWL is required for full payment, the value of the lower specification limit in each of the three cases was set at a value, L, such that 90 percent of the population was above L. The corresponding values from Figure 3.4 for L are 96.9, 96.3, and 96.5 respectively.

It is difficult to say which of the three cases presented in Figure 3.4 should be used by FAA to determine its specification limit. According to the FAA Eastern Region Engineering Bulletin No. 11 (18), the standard deviation value of 1.3 was an estimated value based on the best information available at the time rather than on an analysis of test results. Since an analysis of test results is now available, the value of 1.2 for standard deviation should be considered the better estimate and should be used to establish the specification limit. Thus, Figure 3.4a or 3.4c should be preferred to Figure 3.4b. The remaining question is which mean value should be used.

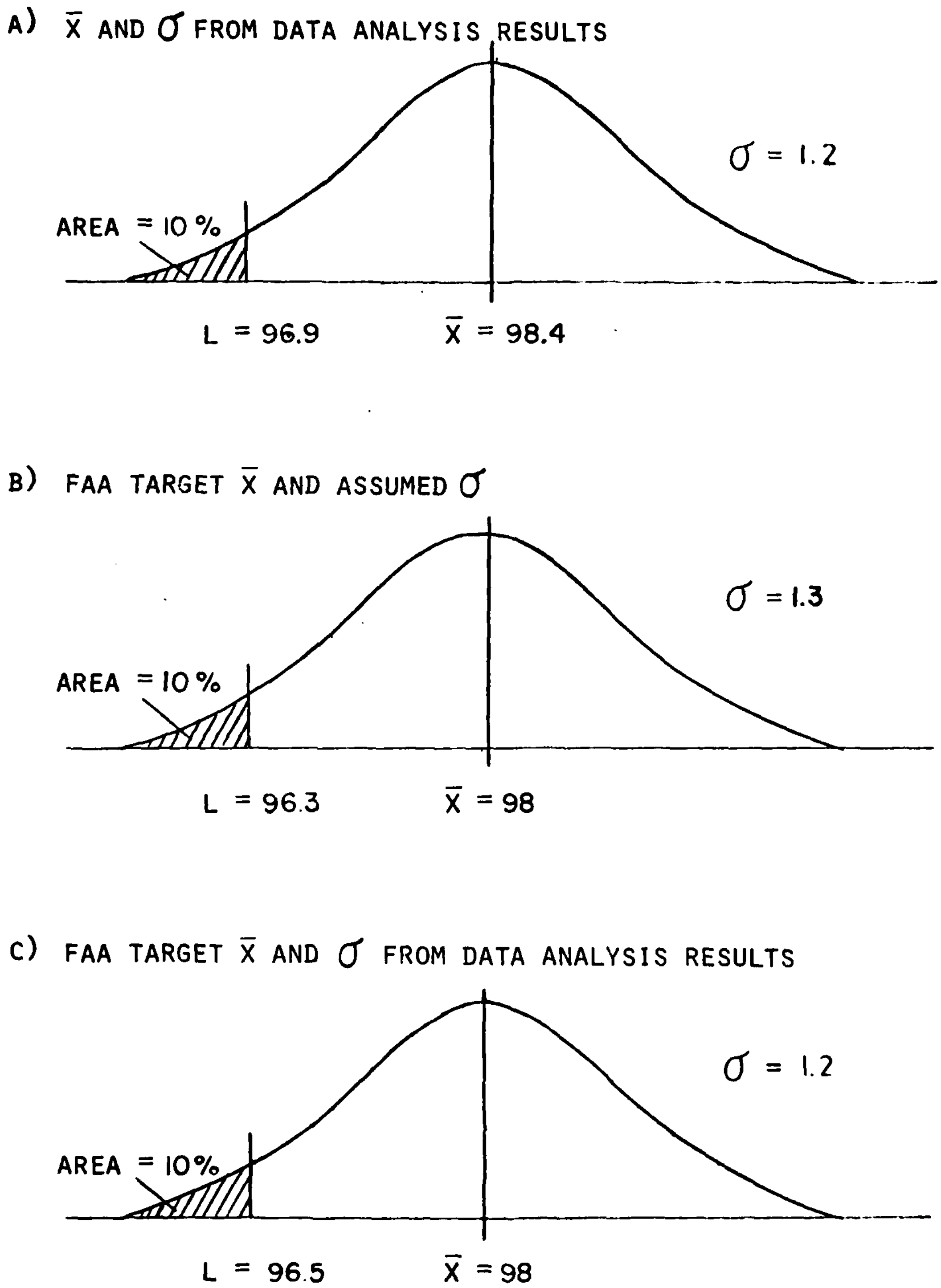


FIGURE 3.4 THREE CASES CONSIDERED IN ESTABLISHING DENSITY SPECIFICATION LIMIT

The mean value of 98.4 percent, derived from the test results, should perhaps be used (a specification limit of 96.9 percent) since this value was achieved in the field. On the other hand, the FAA target value of 98 percent might be used (a specification limit of 96.5 percent) since this value was originally considered acceptable by FAA. According to Engineering Bulletin No. 11 (18):

> The 98 percent requirement was developed in order to limit the in-place air voids in the pavement to 7 percent and to eliminate secondary compaction (rutting) by insuring adequate strength (in-place stability). In other words, 98 percent compaction is necessary to insure adequate strength and durability so that the 20-year life would be realized.

A compromise limit of 96.7 percent, as in the FAA plan of 1978, might also be used. The ultimate decision regarding the specification limit must be made by FAA after the findings presented in this report are reviewed. However, the chosen limit should be used whether acceptance is determined by the density results of four cores or by seven nuclear density readings. The lower limit chosen will not directly affect calculations for OC curves made in this report (for example, Figure 3.2), as long as the curves are presented in terms of actual PWL values.

Type of Acceptance Plan

The first question which had to be addressed was the method of determining acceptance. The method which was selected was the Percent Within Limits (PWL) approach, which had been adopted in the FAA acceptance plan. This type of plan has the advantage of considering both the mean and variability of the material. This approach was used successfully by FAA during the 1978 construction season and had become known by the consultants, testing laboratories, and contractors during the season.

Range Method Versus Standard Deviation Method

The FAA acceptance plan for density, as outlined in the Eastern Region P-401 specification, is based on the Range Method for estimating PWL. In this method a Quality Index, Q, is calculated for each set of samples. For the case of density, which has only a lower specification limit, L, the value of Q_L is calculated from

$$Q_L = \frac{\overline{X}_n - L}{R_n}$$

where: Q_L = Quality Index for lower specification limit

$\overline{X}_n$ = Mean value of n samples in the lot

n = Number of samples in each lot

R_n = Range (difference between largest and smallest) of the n samples in the lot

L = lower specification limit.

Once the value of Q_L has been calculated, the estimate of PWL can be determined from tables that relate Q values to estimated PWL. The table for estimating PWL from the FAA acceptance plan is included in Table 3.4. This table is adapted from Willenbrock and Kopac (8).

It has been pointed out (8) that the range method, which is used in the FAA plan, provides a biased estimate of percent within limits. Willenbrock and Kopac (8) recommend the use of the standard deviation method for estimating percent within limits since:

> it provides unbiased estimates of the percentage within limits.... The standard deviation method also requires smaller sample sizes than the range method in order to provide a given degree of protection.

In light of the better estimate afforded by the standard deviation method, it is recommended that the FAA adopt the standard deviation method in lieu of the range method. The advantage attributed to the range method is that

TABLE 3.4 TABLE FROM FAA EASTERN REGION SPECIFICATIONS FOR ESTIMATING PWL BY THE RANGE METHOD

Percent Above Tolerance Limit	Positive Values of Q_U or Q_L				
	n=3	n=4	n=5	n=6	n=7
99	.5895	.6574	.6642	.6611	.6534
98	.5879	.6440	.6387	.6264	.6124
97	.5863	.6307	.6166	.5983	.5811
96	.5847	.6173	.5966	.5744	.5550
95	.5830	.6039	.5777	.5530	.5319
94	.5814	.5905	.5600	.5330	.5110
93	.5797	.5771	.5431	.5143	.4916
92	.5762	.5638	.5267	.4968	.4735
91	.5719	.5504	.5108	.4800	.4564
90	.5677	.5370	.4955	.4640	.4402
89	.5621	.5236	.4808	.4485	.4249
88	.5564	.5101	.4657	.4337	.4099
87	.5499	.4967	.4514	.4191	.3957
86	.5432	.4833	.4373	.4050	.3817
85	.5355	.4699	.4234	.3913	.3683
84	.5275	.4565	.4097	.3778	.3552
83	.5189	.4431	.3962	.3647	.3424
82	.5098	.4297	.3829	.3517	.3300
81	.5001	.4162	.3697	.3391	.3177
80	.4889	.4028	.3567	.3266	.3058
79	.4791	.3894	.3438	.3144	.2941
78	.4679	.3760	.3311	.3023	.2825
77	.4560	.3626	.3184	.2902	.2712
76	.4439	.3492	.3059	.2786	.2599
75	.4311	.3358	.2935	.2669	.2489
74	.4179	.3223	.2811	.2554	.2380
73	.4041	.3088	.2689	.2440	.2273
72	.3901	.2954	.2567	.2327	.2166
71	.3754	.2820	.2446	.2215	.2061
70	.3604	.2685	.2325	.2104	.1957
69	.3450	.2551	.2206	.1995	.1854
68	.3293	.2417	.2086	.1884	.1752
67	.3131	.2283	.1968	.1777	.1649
66	.2965	.2149	.1835	.1668	.1549
65	.2798	.2015	.1732	.1562	.1450

TABLE 3.4 (CONTINUED)

Percent Above Tolerance Limit	Positive Values of Q_U of Q_L				
	n=3	n=4	n=5	n=6	n=7
64	.2625	.1881	.1614	.1455	.1351
63	.2451	.1747	.1497	.1349	.1252
62	.2274	.1611	.1382	.1243	.1152
61	.2093	.1477	.1265	.1139	.1055
60	.1911	.1343	.1149	.1034	.0957
55	.0970	.0672	.0573	.0515	.0477
50	.0000	.0000	.0000	.0000	.0000

TABLE 3.4 (CONTINUED)

Percent Above Tolerance Limit	Negative Values of Q_U or Q_L				
	n=3	n=4	n=5	n=6	n=7
50	.0000	.0000	.0000	.0000	.0000
45	.0970	.0672	.0573	.0515	.0477
40	.1911	.1343	.1149	.1034	.0957
39	.2093	.1477	.1265	.1139	.1055
38	.2274	.1611	.1382	.1243	.1152
37	.2451	.1747	.1497	.1349	.1252
36	.2625	.1881	.1614	.1455	.1351
35	.2798	.2015	.1732	.1562	.1450
34	.2965	.2149	.1835	.1668	.1549
33	.3131	.2283	.1968	.1777	.1649
32	.3293	.2417	.2086	.1884	.1752
31	.3450	.2551	.2206	.1995	.1854
30	.3604	.2685	.2325	.2104	.1957
29	.3754	.2820	.2446	.2215	.2061
28	.3901	.2954	.2567	.2327	.2166
27	.4041	.3088	.2689	.2440	.2273
26	.4179	.3223	.2811	.2554	.2380
25	.4311	.3358	.2935	.2669	.2489
24	.4439	.3492	.3059	.2785	.2599
23	.4560	.3626	.3184	.2902	.2712
22	.4679	.3760	.3311	.3023	.2825
21	.4791	.3894	.3438	.3144	.2941
20	.4899	.4028	.3567	.3266	.3058
19	.5001	.4162	.3697	.3391	.3177
18	.5098	.4297	.3829	.3517	.3300
17	.5189	.4431	.3962	.3647	.3424
16	.5275	.4565	.4097	.3778	.3552
15	.5355	.4699	.4234	.3913	.3683
14	.5432	.4833	.4373	.4050	.3817
13	.5499	.4967	.4514	.4191	.3957
12	.5564	.5101	.4657	.4337	.4099
11	.5621	.5236	.4808	.4485	.4249
10	.5677	.5370	.4955	.4640	.4402
9	.5719	.5504	.5108	.4800	.4564
8	.5762	.5638	.5267	.4968	.4735
7	.5797	.5771	.5431	.5143	.4916
6	.5814	.5905	.5600	.5330	.5110
5	.5830	.6039	.5777	.5530	.5319
4	.5847	.6173	.5966	.5744	.5550
3	.5863	.6307	.6166	.5983	.5811
2	.5879	.6440	.6387	.6264	.6124
1	.5895	.6574	.6642	.6611	.6534

range is a more easily understood concept. With the advent of inexpensive pocket calculators that provide the capability of quickly determining mean and standard deviation, the researchers consider the use of the range method to be no longer warranted. The standard deviation method was used to determine all OC and Expected Payment curves presented in this report.

The method for estimating PWL in the proposed new acceptance plan is based on the calculation of a Quality Index for the lot by using the standard deviation method. The Quality Index, Q_L, for density can be calculated from

$$Q_L = \frac{\overline{X}_n - L}{S_n}$$

where: Q_L, $\overline{X}_n$, n, and L are defined as before

S_n = Standard deviation of n samples in the lot,

and S_n can be calculated from

$$S_n = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X}_n)^2}{n-1}}$$

where: X_i, i = 1,2,3 ....n = individual sample results

n = number of samples in each lot.

As in the case of the range method, once Q_L has been calculated by the standard deviation method, the estimated value of PWL can be determined from tabled values of Q. An appropriate table, from Willenbrock and Kopac (8), for the standard deviation method is given in Table 3.5.

Price Adjustments--Continuous Versus Discrete

The price adjustment schedule from the FAA acceptance plan is given in Table 3.2, and is shown graphically in Figure 3.5. This type of schedule

TABLE 3.5 TABLE FOR ESTIMATING PERCENT OF LOT WITHIN LIMITS (PWL)
(STANDARD DEVIATION METHOD) (8)

Percent Within Limits	Negative Values of Q_U or Q_L					Percent Within Limits	Positive Values of Q_U or Q_L				
	n=3	n=4	n=5	n=6	n=7		n=3	n=4	n=5	n=6	n=7
50	.0000	.0000	.0000	.0000	.0000	99	1.1510	1.4700	1.6719	1.8016	1.8893
45	.1806	.1500	.1406	.1364	.1338	98	1.1476	1.4400	1.6018	1.6990	1.7615
						97	1.1439	1.4100	1.5428	1.6190	1.6662
40	.3568	.3000	.2823	.2740	.2689	96	1.1402	1.3800	1.4898	1.5500	1.5868
39	.3912	.3300	.3106	.3018	.2966	95	1.1367	1.3500	1.4408	1.4892	1.5184
38	.4252	.3600	.3392	.3295	.3238						
37	.4587	.3900	.3678	.3577	.3515	94	1.1330	1.3200	1.3946	1.4332	1.4562
36	.4917	.4200	.3968	.3859	.3791	93	1.1263	1.2900	1.3510	1.3813	1.3990
						92	1.1170	1.2600	1.3091	1.3328	1.3465
35	.5242	.4500	.4254	.4140	.4073	91	1.1087	1.2300	1.2683	1.2866	1.2966
34	.5564	.4800	.4544	.4426	.4354	90	1.0977	1.2000	1.2293	1.2421	1.2494
33	.5878	.5100	.4837	.4712	.4639						
32	.6187	.5400	.5131	.5002	.4925	89	1.0864	1.1700	1.1911	1.2001	1.2045
31	.6490	.5700	.5424	.5292	.5211	88	1.0732	1.1400	1.1538	1.1592	1.1615
						87	1.0596	1.1100	1.1174	1.1196	1.1202
30	.6788	.6000	.5717	.5586	.5506	86	1.0446	1.0800	1.0819	1.0813	1.0798
29	.7076	.6300	.6018	.5880	.5846	85	1.0286	1.0500	1.0469	1.0437	1.0413
28	.7360	.6600	.6315	.6178	.6095						
27	.7635	.6900	.6619	.6480	.6395	84	1.0118	1.0200	1.0125	1.0073	1.0032
26	.7905	.7200	.6919	.6782	.6703	83	.9940	.9900	.9782	.9718	.9673
						82	.9748	.9600	.9453	.9367	.9315
25	.8164	.7500	.7227	.7093	.7011	81	.9555	.9300	.9123	.9028	.8966
24	.8416	.7800	.7535	.7403	.7320	80	.9342	.9000	.8798	.8693	.8626
23	.8661	.8100	.7846	.7717	.7642						
22	.8896	.8400	.8161	.8040	.7964	79	.9122	.8700	.8479	.8363	.8290
21	.9122	.8700	.8479	.8363	.8290	78	.8896	.8400	.8161	.8040	.7964
						77	.8661	.8100	.7846	.7717	.7642
						76	.8416	.7800	.7535	.7403	.7320
						75	.8164	.7500	.7227	.7093	.7011

TABLE 3.5 (CONTINUED)

Percent Within Limits	Negative Values of Q_U or Q_L					Percent Within Limits	Positive Values of Q_U or Q_L				
	n=3	n=4	n=5	n=6	n=7		n=3	n=4	n=5	n=6	n=7
20	.9342	.9000	.8798	.8693	.8626	74	.7905	.7200	.6919	.6782	.6703
19	.9555	.9300	.9123	.9028	.8966	73	.7635	.6900	.6619	.6480	.6395
18	.9748	.9600	.9453	.9367	.9315	72	.7360	.6600	.6315	.6178	.6095
17	.9940	.9900	.9782	.9718	.9673	71	.7076	.6300	.6018	.5880	.5846
16	1.0118	1.0200	1.0125	1.0073	1.0032	70	.6788	.6000	.5717	.5586	.5506
15	1.0286	1.0500	1.0469	1.0437	1.0413	69	.6490	.5700	.5424	.5292	.5211
14	1.0446	1.0800	1.0819	1.0813	1.0798	68	.6187	.5400	.5131	.5002	.4925
13	1.0597	1.1100	1.1174	1.1196	1.1202	67	.5878	.5100	.4837	.4712	.4639
12	1.0732	1.1400	1.1538	1.1592	1.1615	66	.5564	.4800	.4544	.4426	.4354
11	1.0864	1.1700	1.1911	1.2001	1.2045	65	.5242	.4500	.4254	.4140	.4073
10	1.0977	1.2000	1.2293	1.2421	1.2494	64	.4917	.4200	.3968	.3859	.3791
9	1.1087	1.2300	1.2683	1.2866	1.2966	63	.4587	.3900	.3678	.3577	.3515
8	1.1170	1.2600	1.3091	1.3328	1.3465	62	.4252	.3600	.3392	.3295	.3238
7	1.1263	1.2900	1.3510	1.3813	1.3990	61	.3912	.3300	.3106	.3018	.2966
6	1.1330	1.3200	1.3946	1.4332	1.4562	60	.3568	.3000	.2823	.2740	.2689
5	1.1367	1.3500	1.4408	1.4892	1.5184	55	.1806	.1500	.1406	.1364	.1338
4	1.1402	1.3800	1.4898	1.5500	1.5868	50	.0000	.0000	.0000	.0000	.0000
3	1.1439	1.4100	1.5428	1.6190	1.6662						
2	1.1476	1.4400	1.6018	1.6990	1.7615						
1	1.1510	1.4700	1.6719	1.8016	1.8893						

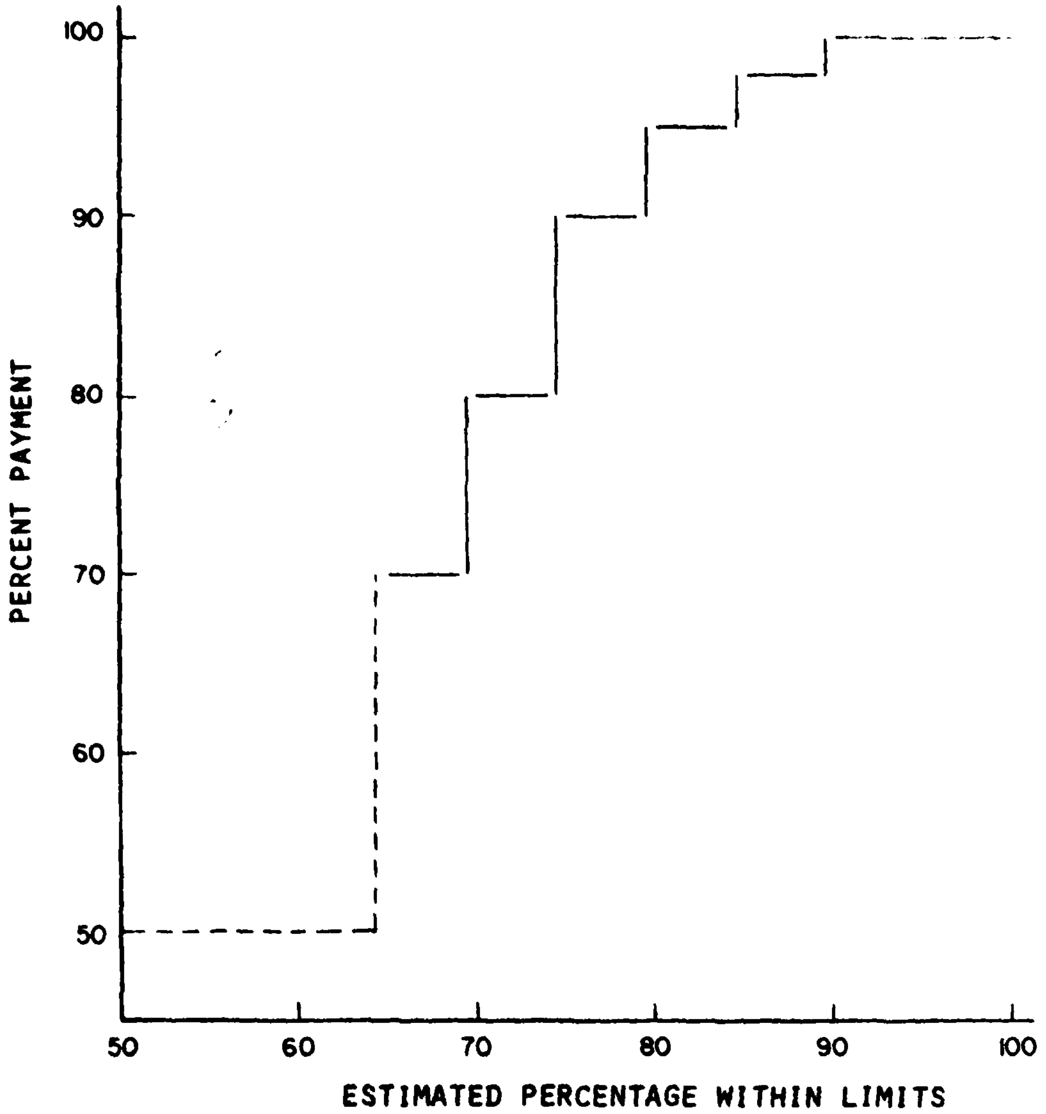


FIGURE 3.5 PRICE ADJUSTMENT SCHEDULE FROM THE FAA DENSITY ACCEPTANCE PLAN

works quite well in the long run, as was shown by the expected payment curve in Figure 3.4. However, this schedule can present some problems in the short run and, in particular, on smaller projects. There are two potential problems with the current FAA price adjustment schedule.

The first problem deals with the uncertain area between different pay levels. Table 3.2 indicates that material which is 90-100 percent within limits is to receive 100 percent payment, and that material which is 85-89 percent within limits is to be paid for at 98 percent of the contract price. This could present problems of interpretation when the estimated PWL is between 89 and 90. These potential areas of uncertainty occur at the boundary of each price adjustment level, and are indicated by gaps in the plot in Figure 3.5.

Another area of concern is the large incremental differences in the price adjustment levels. A situation in which, for example, 75.1 PWL is worth 90 percent payment while 74.9 PWL (or 74.4) is worth only 80 percent payment, is a difficult one, particularly in light of the uncertain areas between price adjustment levels. It can be argued that in the long run these situations, i.e. 74.9 vs 75.1 PWL, will balance out, as shown by the expected payment curve in Figure 3.4. But on a small project or in the case of a contractor who works infrequently under the FAA acceptance plan, there is no long run in which this balancing effect can take place. It is suggested that a continuous, rather than discrete, price adjustment schedule would eliminate potential problems when the estimated PWL is near the boundary between price adjustment levels. Willenbrock and Kopac (8) have recommended that a specifying agency:

seriously consider the use of a continuous price adjustment schedule which can be presented in a graphical fashion or as a series of straight line equations between the various price adjustment levels. This approach would eliminate a lot of potential field problems of interpretation which could develop.

For the reasons stated above, it was decided to use a continuous price adjustment schedule in the proposed new acceptance plan.

Development of Price Adjustments

Since the development of acceptance plans by the OC curve approach requires some subjective analysis and engineering judgment, it was decided to base the continuous price adjustment on the discrete schedule developed by FAA. This was done for two reasons. First, FAA considered it to be a reasonable schedule, and second, as far as the researchers could determine, the schedule had gone through one construction season with no major complaints from the contractors about its fairness.

Five different continuous price adjustment schedules, all based on the FAA schedule, were considered. The five price adjustment schedules (labeled I, II, III, IV, and V) are shown in Figures 3.6 through 3.10. The first three schedules are based on the use of several straight line equations to relate payment level and estimated PWL. The last two schedules attempted to fit one curved line to the FAA schedule to eliminate the need for more than one equation. These curves were fitted to the FAA plan by multiple regression analysis. In the regression analysis, percent payment level from the FAA schedule was used as the dependent variable, and selected values of estimated PWL were used as the independent variable. The points used in the regression analyses are indicated in Figures 3.9 and 3.10. To choose among these five schedules, it was decided to compare their OC curves and curves of expected payment with those of the FAA price adjustment schedule.

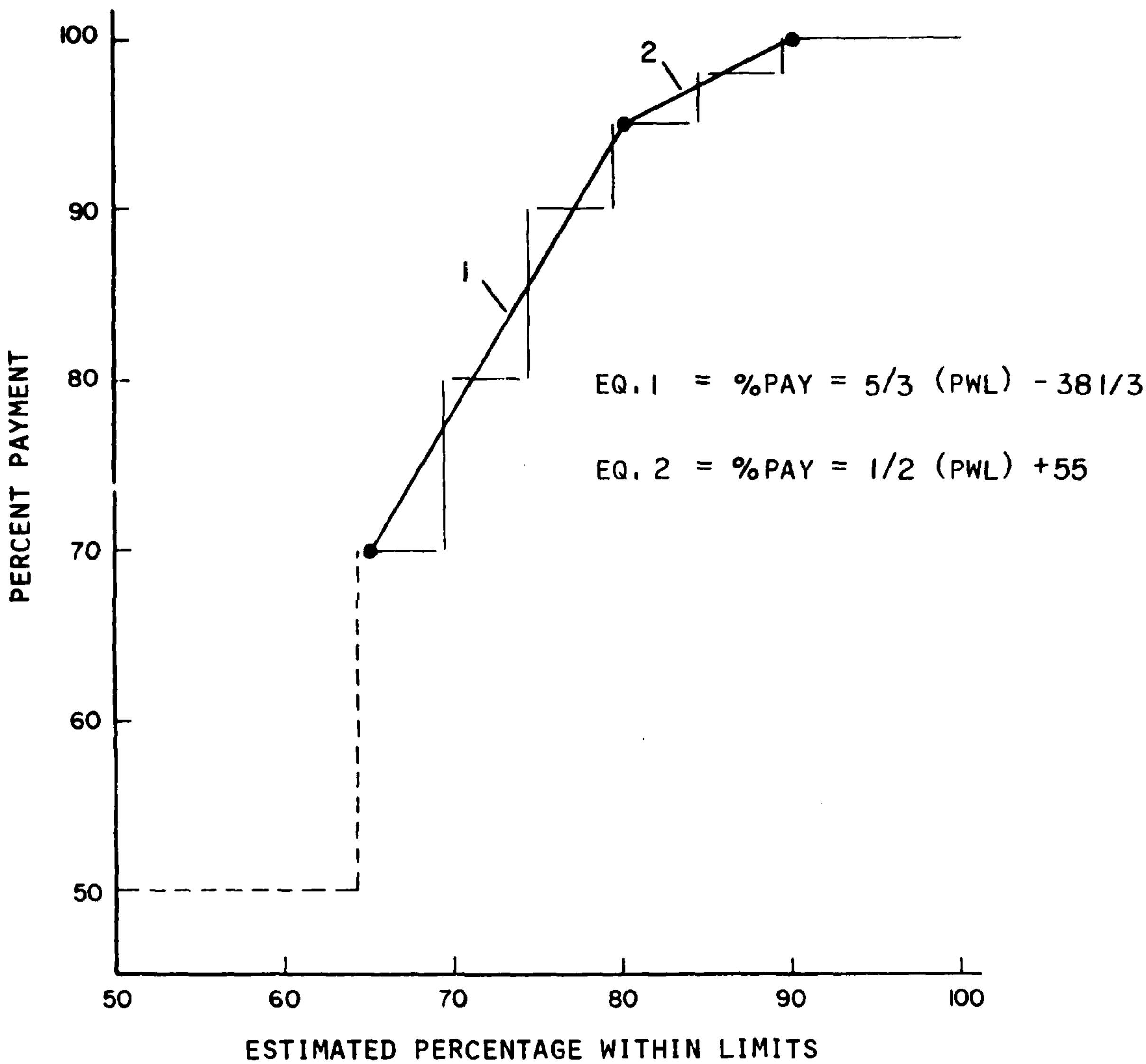


FIGURE 3.6 PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULE I

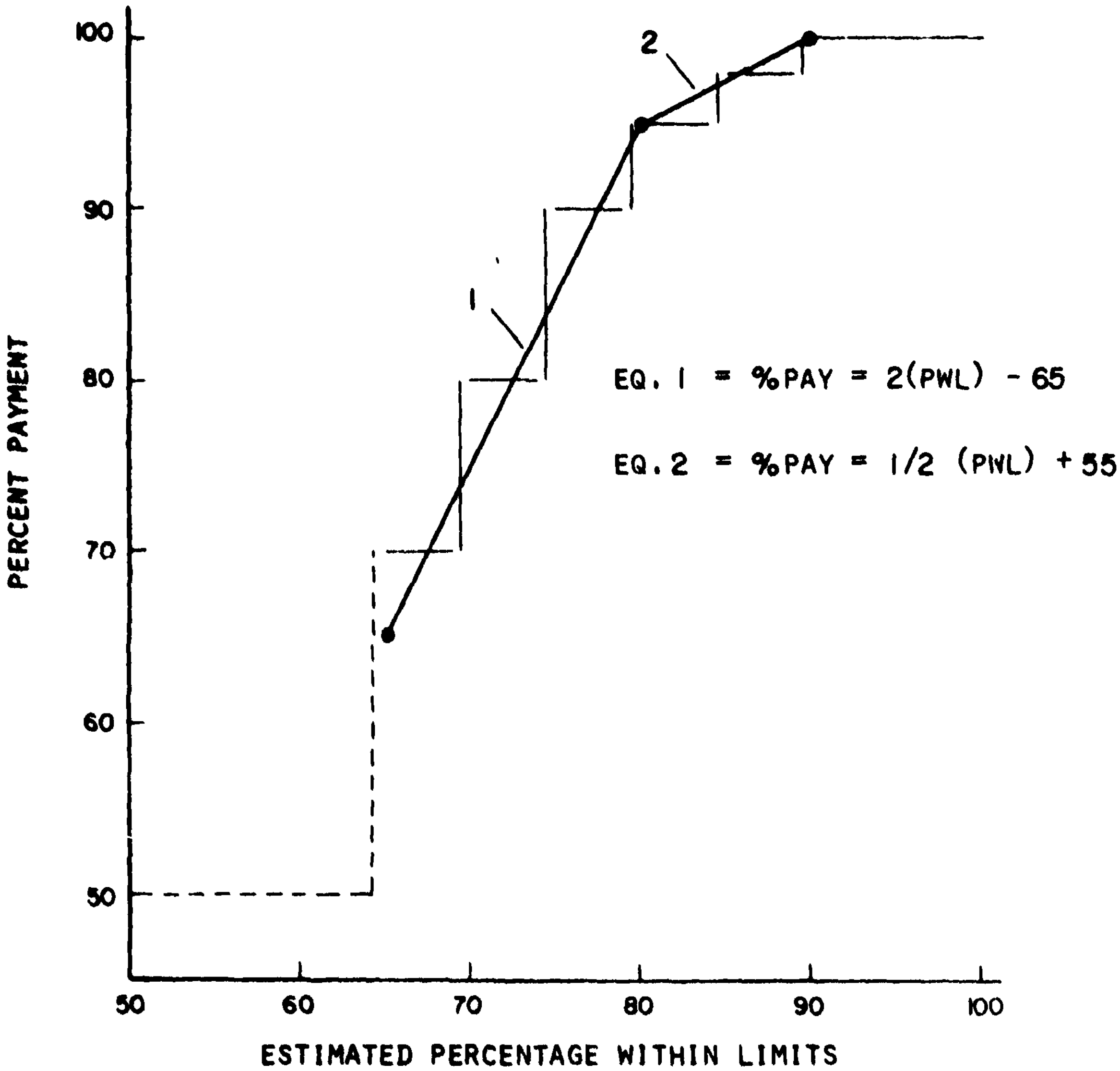


FIGURE 3.7 PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULE II

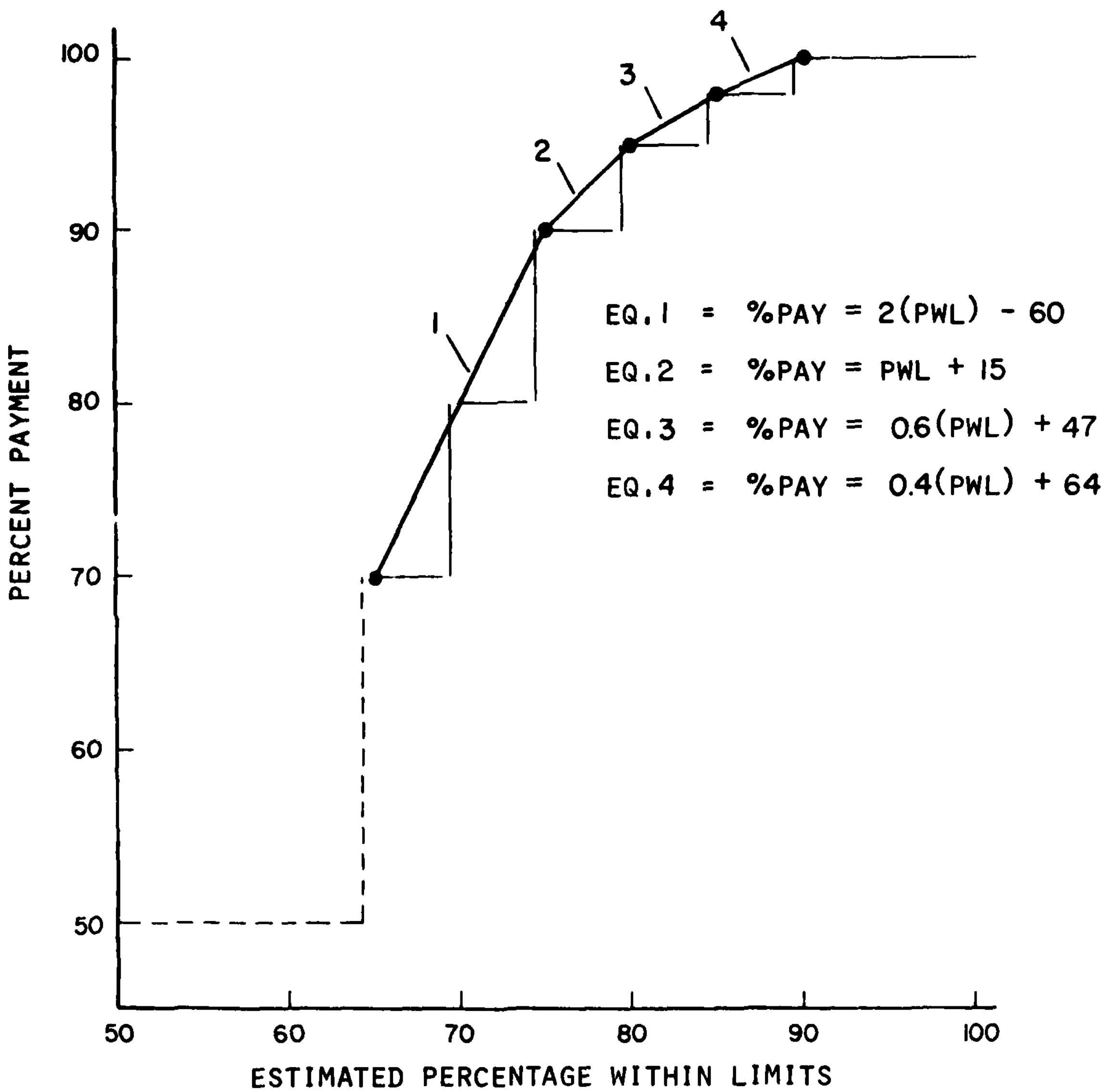


FIGURE 3.8 PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULE III

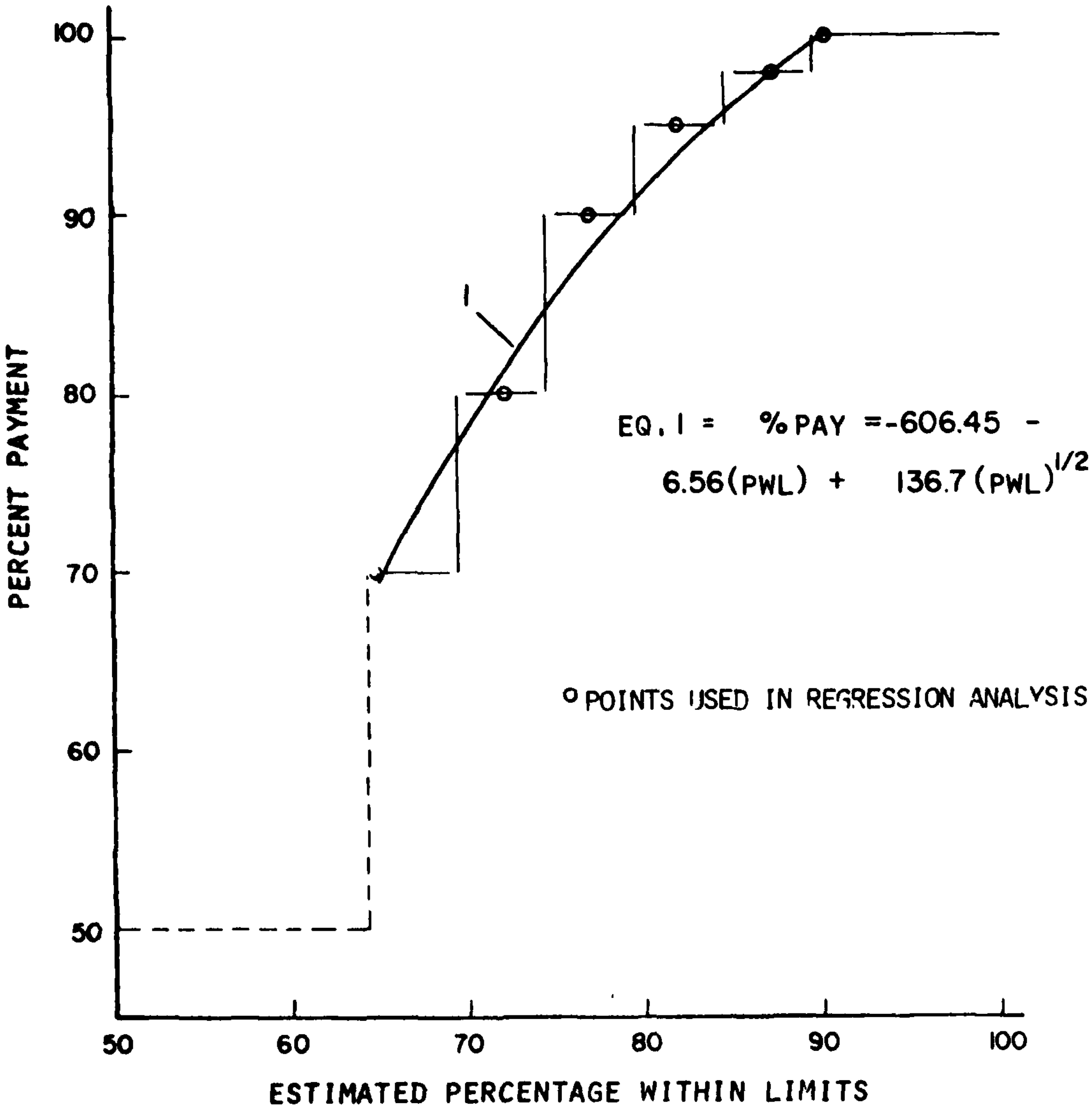


FIGURE 3.9 PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULE IV

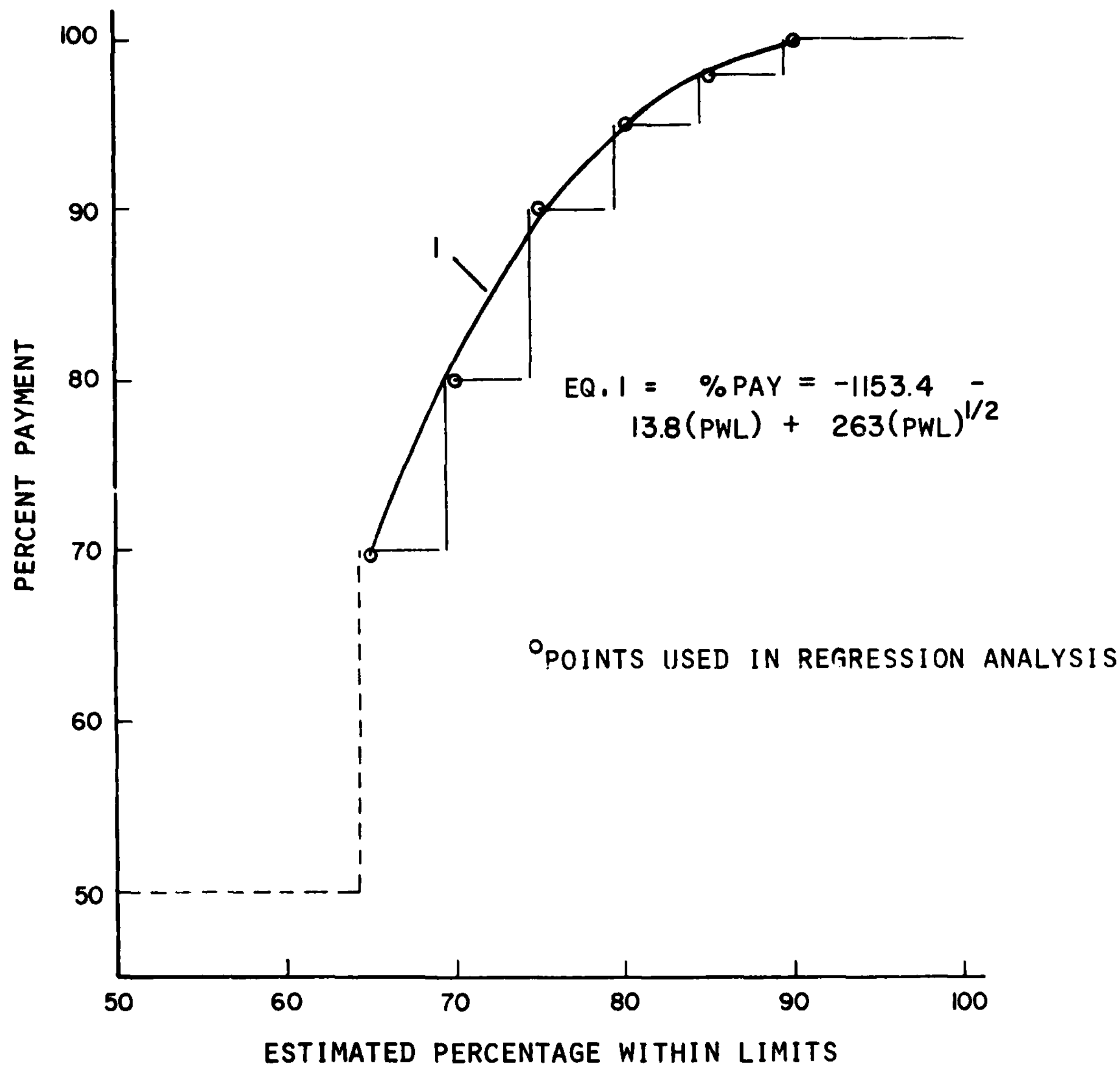


FIGURE 3.10 PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULE V

It has been shown by Resnikoff and Lieberman (19, 20) that non-central t-distribution is appropriate for the estimate of the proportion of a normal population which lies above a given limit. This is the case for the density acceptance plan, in which acceptance is based on an estimate of the proportion (or percentage) of the population which falls above the specification limit. A detailed discussion of the use of the non-central t-distribution to estimate PWL for the case of asphaltic concrete density is presented by Willenbrock and Kopac (9)

The OC curves for the FAA price adjustment schedule and the proposed new schedules were determined by use of a computer program which calculates the area beneath the non-central t-distribution. This program was subroutine MDTN, obtained from the International Mathematical and Statistical Library (IMSL) of Subprograms (21). This subroutine, which is available only in single precision in IMSL, was modified for double precision by Terry L. King, a graduate student in the Department of Statistics at The Pennsylvania State University.

The set of OC curves for the FAA acceptance plan has been presented in Figure 3.2. For the case of the discrete FAA price adjustment schedule, an OC curve can be developed for each price adjustment level. For the case of a continuous price adjustment schedule, there are an infinite number of OC curves possible since there are an infinite number of potential payment levels. The operating characteristics for the case of a continuous schedule can therefore be indicated by a region which has as its bounds a curve corresponding to the probability of receiving 100 percent payment and another curve corresponding to the probability of receiving at least the minimum possible payment. For each of the five proposed schedules, 100 percent

payment occurs at an estimated PWL value ($\widehat{PWL}$) of 90 or greater, and the minimum payment level occurs at a $\widehat{PWL}$ of 65. The operating characteristics of the proposed schedules can be represented, then, by a region bounded by one curve corresponding to the probability of $\widehat{PWL}$ greater than or equal to 90 for each actual value of PWL and by another curve corresponding to the probability of $\widehat{PWL}$ greater than or equal to 65 for each actual value of PWL. The region within these curves corresponds to the probability of receiving some payment.

The operating characteristics of the five proposed schedules for sample sizes of four, five, and seven are presented in Figure 3.11. The upper and lower bounds, which correspond to the probability of receiving some payment, are the same for all five plans. The improved estimate associated with increasing the sample size is clearly demonstrated on this figure because the probability of receiving a particular payment becomes higher for the higher quality levels and lower for the lower quality levels as the sample size increases. To help distinguish the five plans, Figure 3.12 presents the curves corresponding to the probability of receiving at least 90 percent payment for a sample size of four, for each proposed payment schedule. Even though the boundaries of the payment region are the same for all five schedules, a particular payment level may occur at a different location within the region. It is difficult to compare the five schedules from OC curves similar to those in Figures 3.11 and 3.12. In order to differentiate the five schedules, their expected payment curves must be determined.

For the discrete FAA price adjustment schedule the expected payment curve shown in Figure 3.3 can be calculated from the relationship:

$$\text{Expected Payment} = \sum_{\text{all } i} X_i \, P(X_i)$$

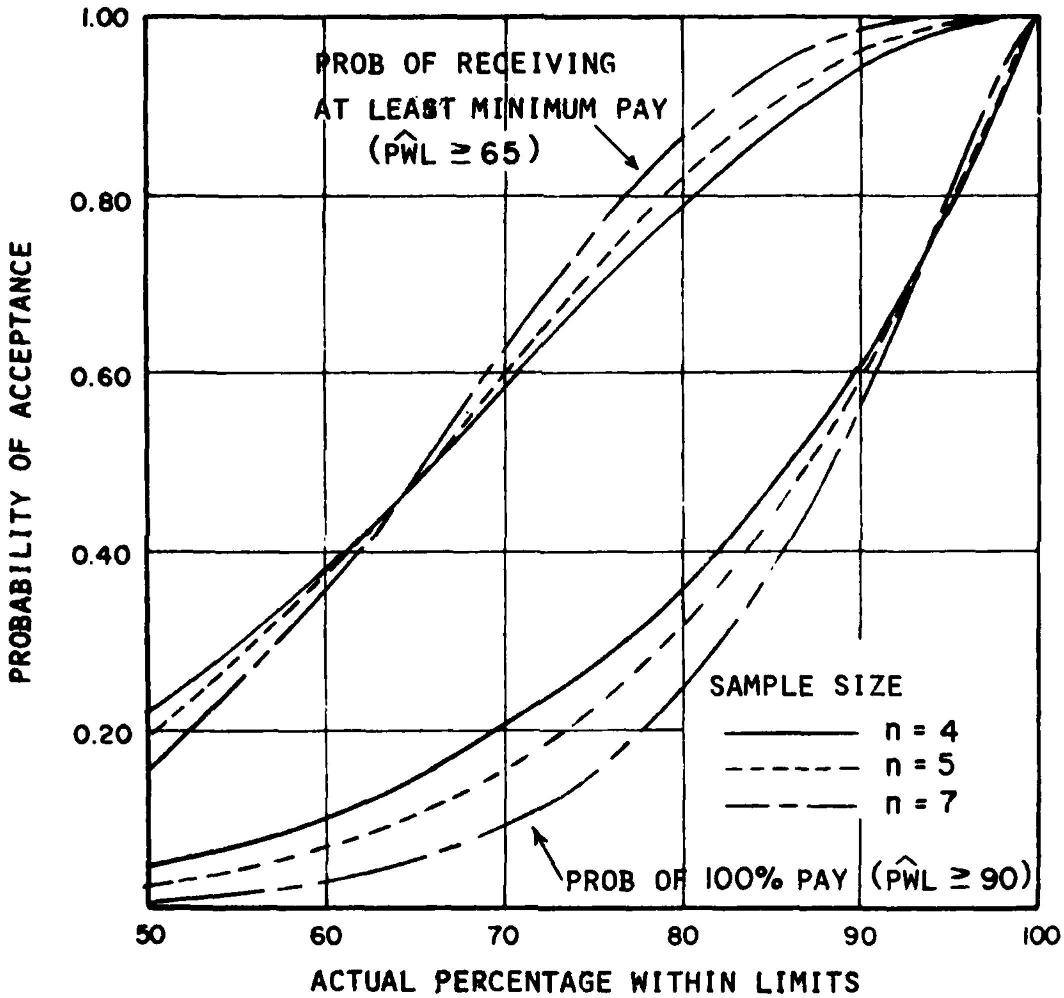


FIGURE 3.11 OPERATING CHARACTERISTICS FOR THE PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULES

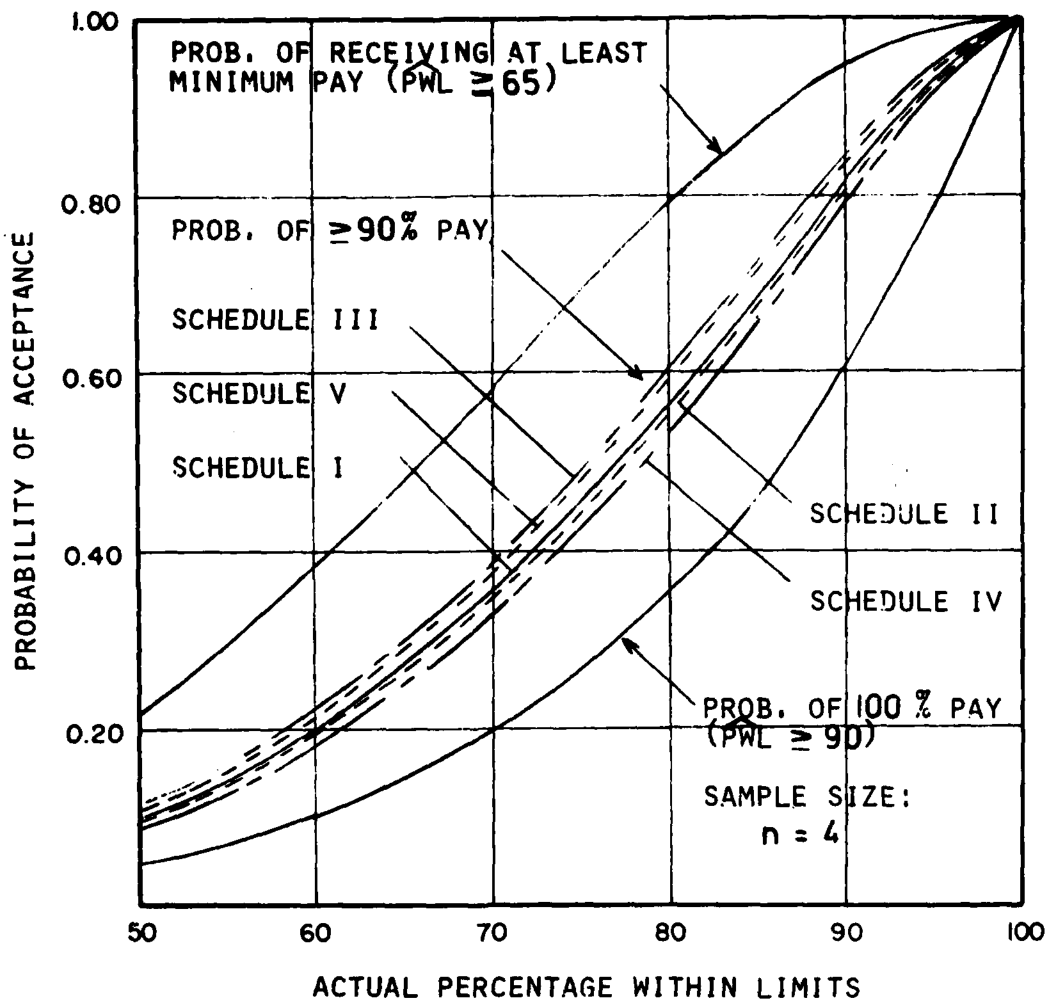


Figure 3.12. OPERATING CHARACTERISTICS CURVES FOR THE PROBABILITY OF RECEIVING MINIMUM, 90 PERCENT, and 100 PERCENT PAYMENT FOR THE PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULES FOR A SAMPLE SIZE OF FOUR.

where: X_i = payment level i.

$P(X_i)$ = probability of receiving payment level i.

The calculations for a sample size of four are shown in Table 3.3.

With a continuous price-adjustment schedule, an integration procedure must be used since the number of possible price adjustment levels is infinite. The expected payment in this case can be calculated from the relationship:

$$\text{Expected Payment} = \int_{-\infty}^{\infty} G(X)\ P(X)\ dX$$

where: X = the estimated PWL value ($\widehat{PWL}$)

G(X) = a payoff function relating the estimated PWL value ($\widehat{PWL}$) to the payment level

P(X) = the probability density function of the estimated PWL values ($\widehat{PWL}$)

This integral is not easy to evaluate by analytical methods. As a convenient approximation to this integral, the potential PWL values were partitioned into small intervals, leading to the following:

$$\text{Expected Payment} = \int_{-\infty}^{65} G(X)\ P(X)\ dX + \int_{65}^{65+\Delta} G(X)\ P(X)\ dX + \ldots.$$

$$\ldots + \int_{90-\Delta}^{90} G(X)\ P(X)\ dX + \int_{90}^{\infty} G(X)\ P(X)\ dX$$

where: Δ = width of the intervals.

In order to simplify the above integrals, it was assumed that for the small intervals involved, the payoff function, G(X), could be replaced by the average payoff over the interval. Thus,

$$\text{Expected Payment} = \int_{-\infty}^{65} 50\, P(X)\, dX + \int_{65}^{65+\Delta} G_1\, P(X)\, dX + \ldots.$$

$$\ldots + \int_{90-\Delta}^{90} G_n\, P(X)\, dX + \int_{90}^{\infty} 100\, P(X)\, dX$$

where: G_i, $i=1,2,\ldots n$ = the average payment associated with each of the n intervals.

This equation can be rewritten as:

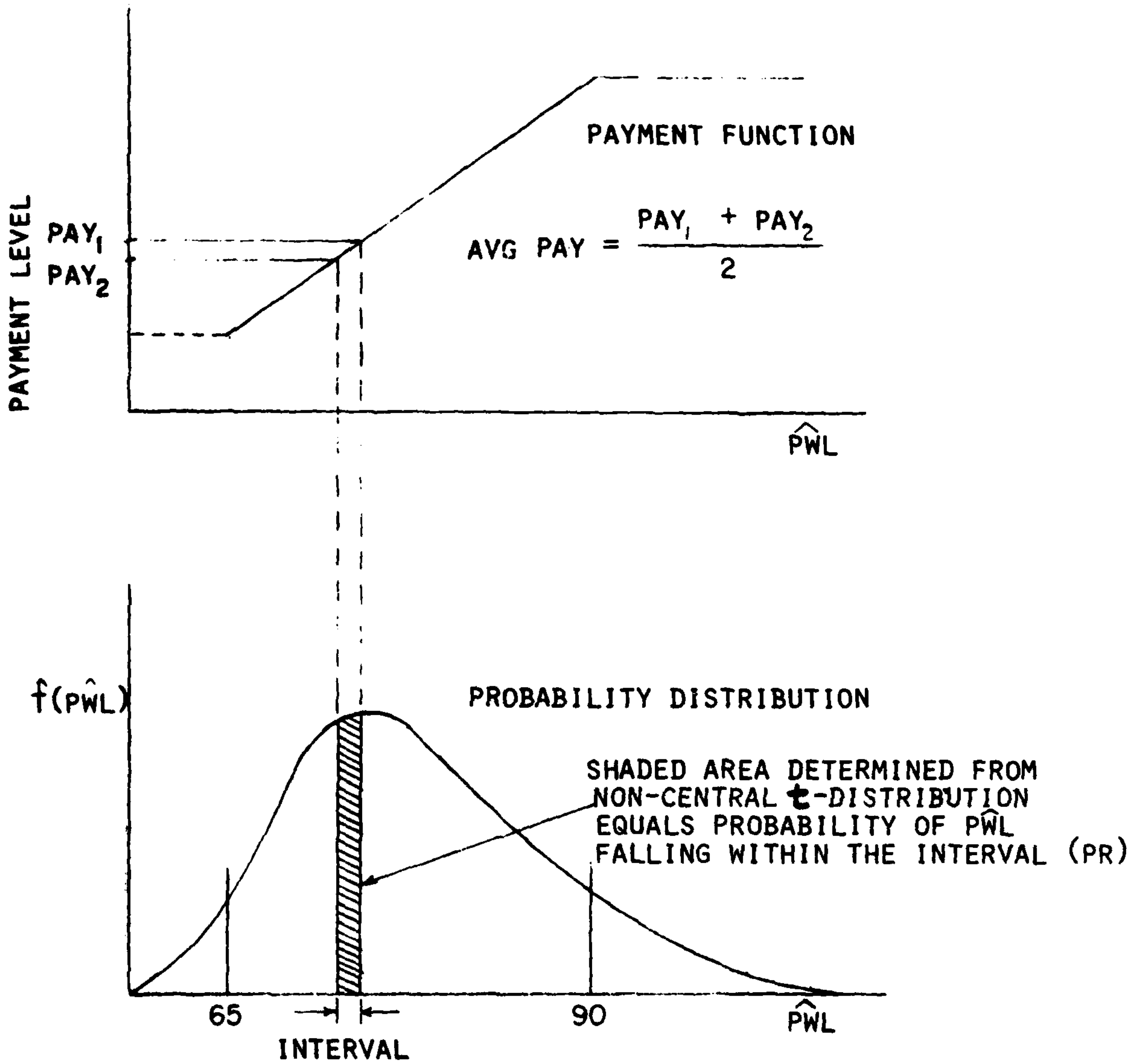
$$\text{Expected Payment} = 50\int_{-\infty}^{65} P(X)\, dX + G_1\int_{65}^{65+\Delta} P(X)\, dX + \ldots.$$

$$\ldots + G_n\int_{90-\Delta}^{90} P(X)\, dX + 100\int_{90}^{\infty} P(X)\, dX.$$

The above integrals can then be evaluated by using subroutine MDTN to determine the appropriate areas under the non-central t-distribution.

To obtain the expected payment curves, a computer program was developed which partitioned the potential $\hat{PWL}$ values into small intervals. Then subroutine MDTN was used to calculate the probability of $\hat{PWL}$ falling within each interval. This probability was multiplied by the average payment associated with that interval, and the products were summed for all of the intervals to achieve a good estimate of the expected payment. This procedure, which was performed for six actual $\hat{PWL}$ values to identify the expected payment curve, is illustrated graphically in Figure 3.13.

The area corresponding to a $\hat{PWL}$ greater than 65 but less than 90 is the probability of receiving some reduced payment; the area falling above a $\hat{PWL}$ of 90 is the probability of receiving 100 percent payment; that falling below a $\hat{PWL}$ of 65 is the probability that the material will have to be either removed and replaced, or accepted as is at a payment of 50 percent. In determining the expected payment curves for the proposed



NOTE: EXPECTED PAYMENT EQUALS THE SUMMATION OF THE PR TIMES AVG PAY FOR ALL INTERVALS

FIGURE 3.13 PROCEDURE USED TO DETERMINE EXPECTED PAYMENT CURVES FOR PROPOSED PRICE ADJUSTMENT SCHEDULES

schedules, the same assumptions concerning the 50 percent payment level were made as were made in the calculation of the expected payment curve for the FAA plan presented in Table 3.3.

To determine the expected payments associated with the partial payment levels, two cases were considered for Price Adjustment Schedule I. The region between $\widehat{PWL}$ equal to 65 and $\widehat{PWL}$ equal to 90 was partitioned into 25 and 50 intervals for the two cases. The expected values were then calculated for both cases and compared. At all actual PWL values tested for the two cases, the expected values calculated using 25 intervals and 50 intervals were identical to four significant figures. It was therefore decided that the results obtained by using 25 intervals were sufficiently accurate. The expected payment curves for sample sizes of four, five, and seven were then calculated using 25 intervals. The results of the calculations for each of the five proposed schedules are presented in Table 3.6. The PWL values included in the table were arbitrarily selected in order to encompass the total range of probable PWL values. Schedules II and IV have expected payment values that are very similar to those of the FAA plan (Table 3.6). The differences between these schedules and the FAA schedule are quite small for the PWL values included in the table. These schedules deviate less from the FAA schedule than do the other three schedules, with Schedule II providing the closest match. The expected payment curves for the FAA schedule and Schedules II and IV are shown in Figures 3.14 through 3.16 for sample sizes of four, five, and seven, respectively. The curves for all three schedules are very similar, and it is difficult to discriminate among them.

TABLE 3.6 SUMMARY OF EXPECTED PAYMENT CURVES FOR PROPOSED DENSITY PRICE ADJUSTMENT SCHEDULES

Sample Size, n=4

Actual PWL	FAA	I	Δ*	II	Δ	III	Δ	IV	Δ	V	Δ	Assumed Value**
98	99.39	99.51	+ .12	99.47	+.08	99.56	+ .17	99.39	.00	99.58	+ .19	100
90	93.66	94.24	+ .58	93.85	+.19	94.59	+ .93	93.78	+.12	94.66	+1.00	100
80	82.42	82.94	+ .52	82.25	-.17	83.45	+1.03	82.40	-.02	83.57	+1.15	90
70	67.89	68.69	+ .80	67.97	+.08	69.17	+1.28	68.24	+.34	69.29	+1.40	75
60	56.58	57.19	+ .61	56.61	+.03	57.54	+ .96	56.88	+.30	57.63	+1.05	75
50	48.00	48.39	+ .39	48.00	.00	48.60	+ .60	48.21	+.21	48.67	+ .67	75
$\Sigma\ (\Delta)^2$			1.79		0.08		4.87		0.26		5.87	

Sample Size, n=5

Actual PWL	FAA	I	Δ*	II	Δ	III	Δ	IV	Δ	V	Δ	Assumed Value**
98	99.63	99.72	+ .09	99.71	+.08	99.76	+ .13	99.63	.00	99.77	+ .14	100
90	94.84	95.44	+ .60	95.11	+.27	95.79	+ .94	94.92	+.08	95.87	+1.03	100
80	83.70	84.33	+ .63	83.59	-.11	84.92	+1.22	83.67	-.03	85.06	+1.36	90
70	68.31	69.24	+ .93	68.42	+.11	69.80	+1.49	68.70	+.39	69.94	+1.63	75
60	55.78	56.47	+ .69	55.81	+.03	56.86	+1.08	56.12	+.34	56.97	+1.19	75
50	46.65	47.05	+ .40	46.65	.00	47.27	+ .65	46.88	+.23	47.34	+ .69	75
$\Sigma\ (\Delta)^2$			2.27		0.10		6.20		0.33		7.48	

TABLE 3.6 (CONTINUED)

	Sample Size, n=7											
Actual PWL	FAA	I	Δ*	II	Δ	III	Δ	IV	Δ	V	Δ	Assumed Value**
98	99.82	99.88	+ .06	99.88	+.06	99.90	+ .08	99.84	+.08	99.91	+ .09	100
90	96.47	96.78	+ .31	96.53	+.06	97.11	+ .64	96.21	-.26	97.18	+ .71	100
80	85.30	86.14	+ .84	85.32	+.02	86.84	+1.54	85.31	+.01	86.99	+1.69	90
70	68.63	69.75	+1.12	68.75	+.12	70.42	+1.79	69.10	+.47	70.59	+1.96	75
60	54.21	54.97	+ .76	54.22	+.01	55.41	+1.20	54.62	+.41	55.53	+1.32	75
50	44.51	44.89	+ .38	44.48	-.03	45.08	+ .57	44.73	+.22	45.14	+ .63	75
$(\Delta)^2$			3.47		0.02		7.76		0.51		9.35	

*Δ equals the difference between the value from the schedule under consideration and that from the FAA schedule. i.e. $\Delta = (X_i - X_{FAA})$.

**Assumed percentage of the time that 50 percent payment is received when estimated PWL is below 65.

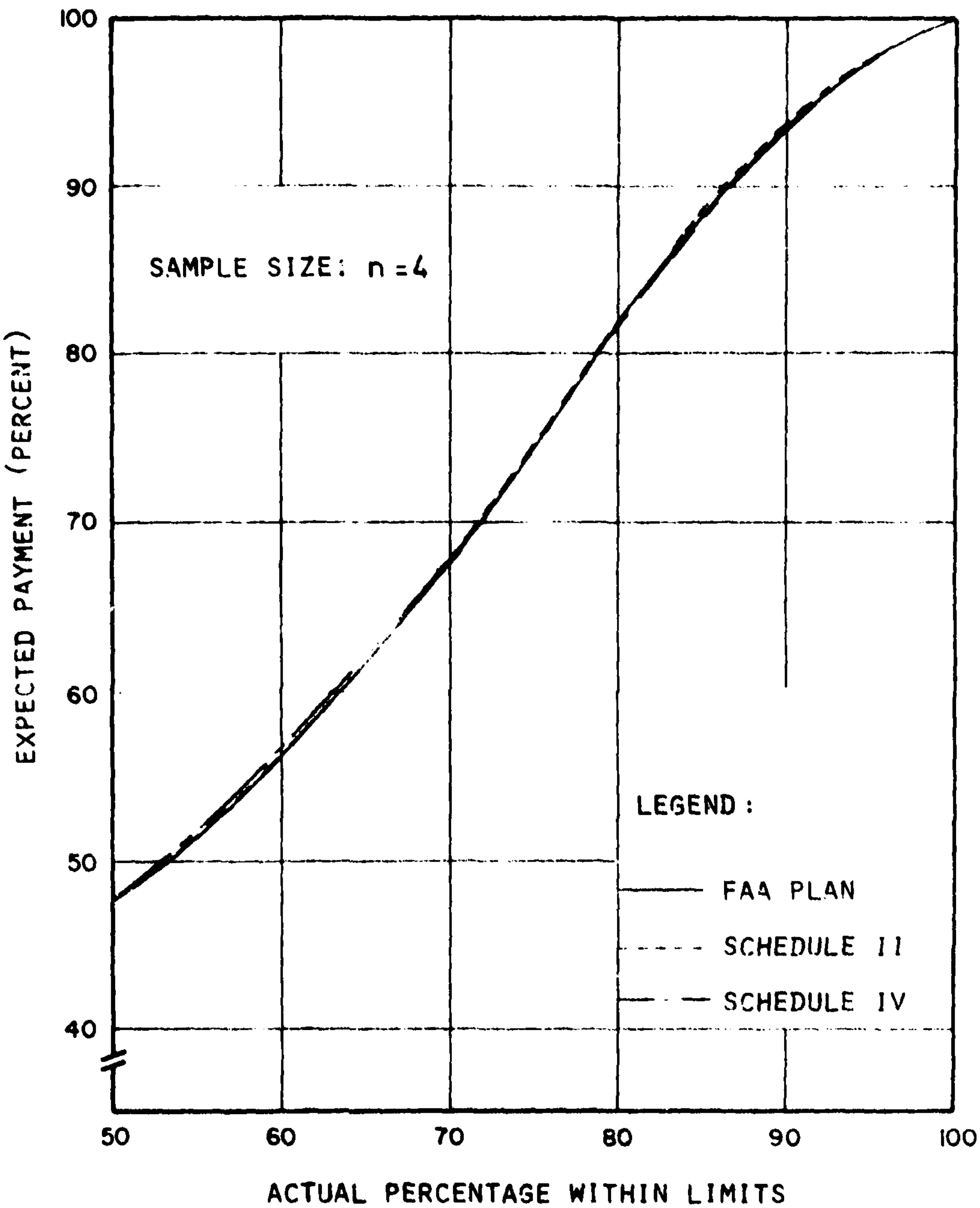


Figure 3.14 EXPECTED PAYMENT CURVES FOR THE FAA PRICE ADJUSTMENT SCHEDULE, SCHEDULE II AND SCHEDULE IV FOR A SAMPLE SIZE OF FOUR

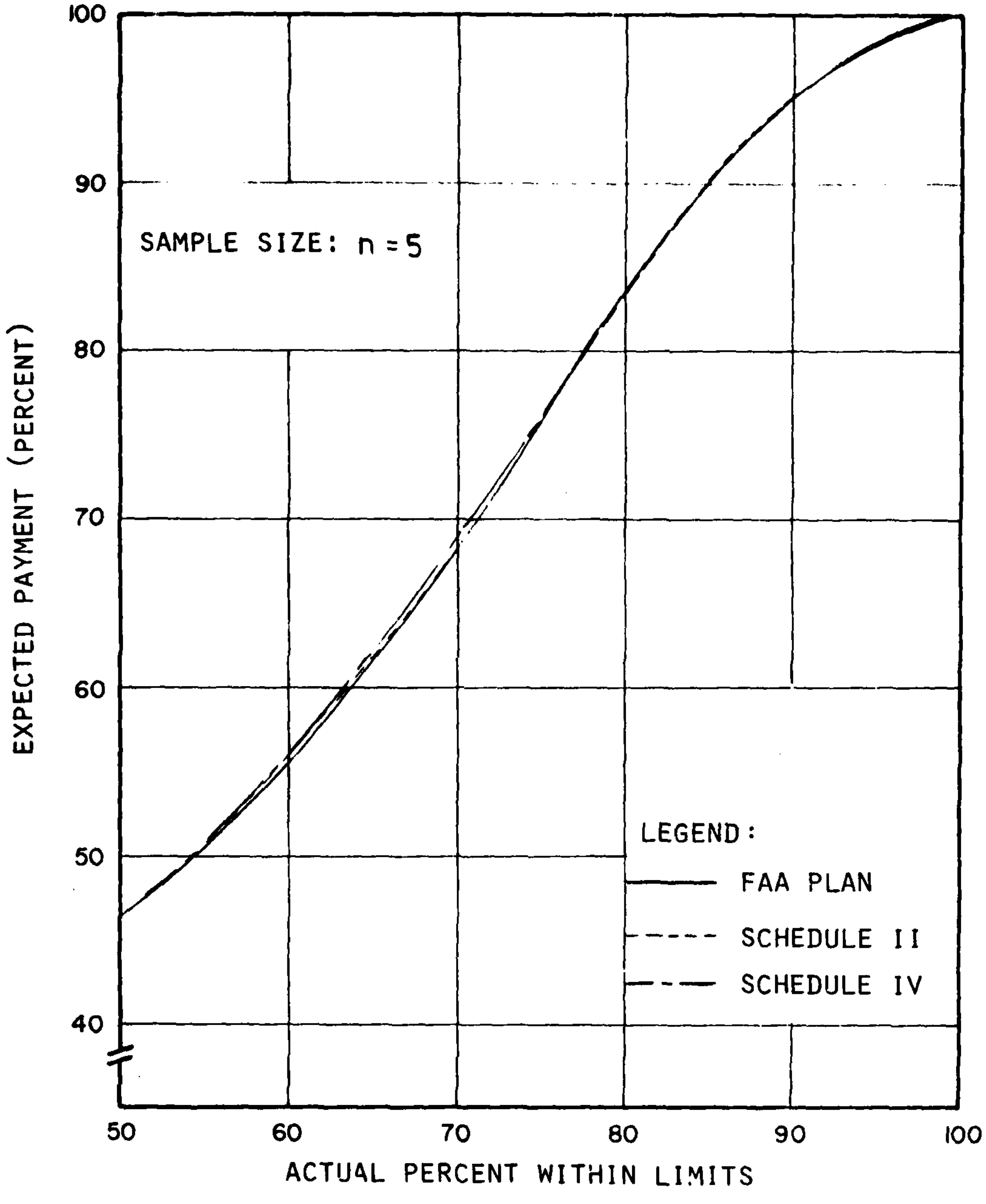


Figure 3.15 EXPECTED PAYMENT CURVES FOR THE FAA SCHEDULE, SCHEDULE II AND SCHEDULE IV FOR A SAMPLE SIZE OF FIVE

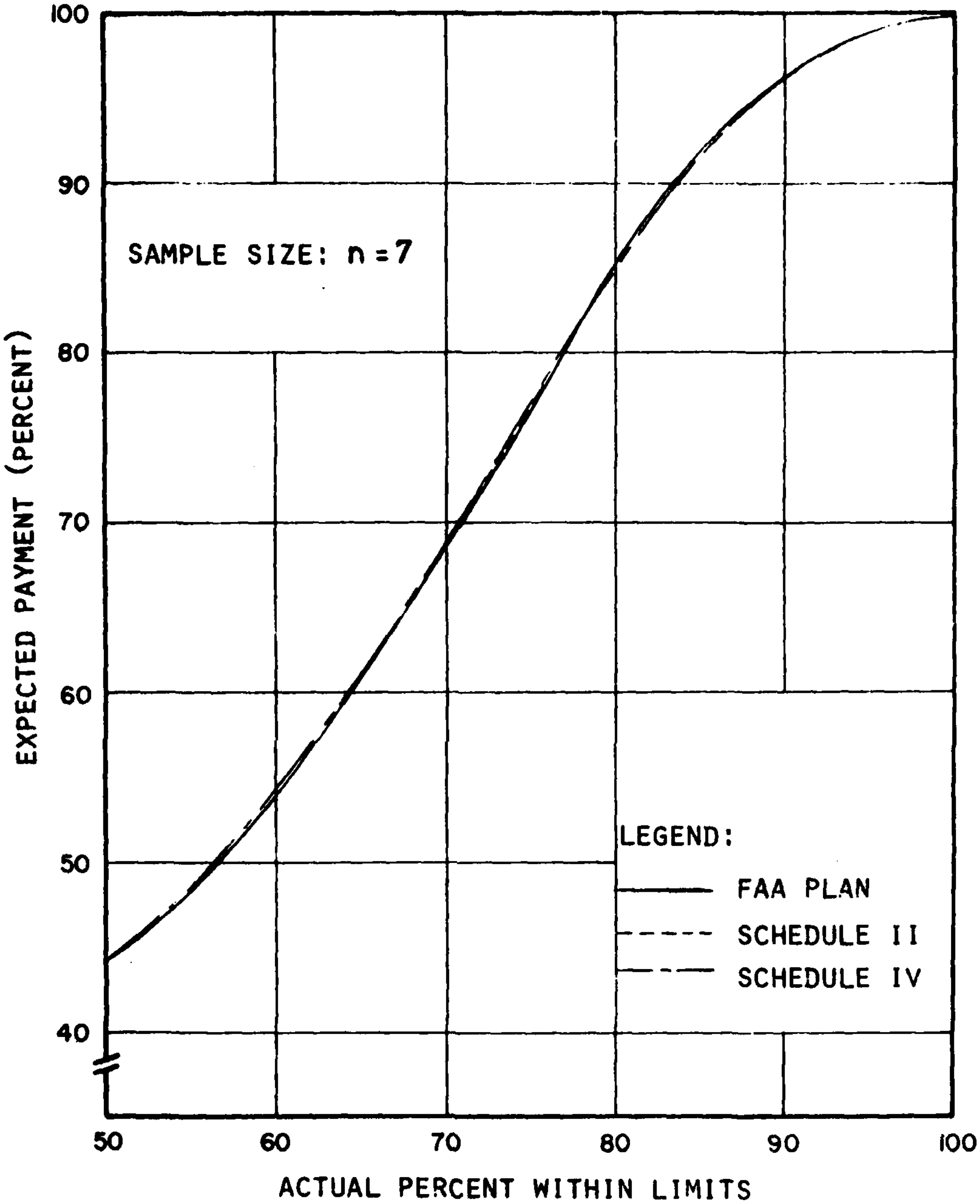


Figure 3.16 EXPECTED PAYMENT CURVES FOR THE FAA SCHEDULE, SCHEDULE II AND SCHEDULE IV FOR A SAMPLE SIZE OF SEVEN

Since the expected payment curves are so similar, the choice between Schedule II and Schedule IV was based on their ease of application in the field. Schedule IV has the advantage of having only one equation, but this equation (Percent Pay = $-606.45 - 6.56$ (PWL) + 136.7 (PWL)$^{1/2}$) is somewhat more complicated than the straight-line equations for Schedule II. For this reason, it was decided to adopt Price Adjustment Schedule II for the proposed new density acceptance plan. The recommended price adjustment schedule is shown in Table 3.7.

Additional OC Curves

In addition to the theoretical development of the OC curves shown in Figures 3.11 and 3.12, additional OC curves were determined by use of computer simulation. The simulation program is discussed in detail in Chapter 4 and in Appendix A.

The use of the computer simulation has an advantage over the theoretical solution. The results of the theoretical solution are presented in terms of the actual PWL of the material. It is difficult for a contractor to relate what is meant by 90 PWL to his construction process. The simulation program allows the operating characteristics to be easily related to the mean density values for a given value of standard deviation. The contractor can determine from past test results what values of mean and standard deviation he can achieve with his process. The simulation program would then allow him to determine OC curves in terms of the mean target value and standard deviation which he is achieving with his process. To do this the contractor must know the price adjustment schedule. Figures 3.17 through 3.19 present OC curves for a sample of size four and a specification limit of 96.7 for standard deviation values of 0.95, 1.19, and 2.00. The value of 1.19 is the pooled standard deviation for all the projects in the study,

TABLE 3.7 PRICE ADJUSTMENT SCHEDULE FOR THE PROPOSED DENSITY ACCEPTANCE PLAN

Estimated Percentage of Material Above the Specification Limit (PWL)	Percent of Contract Price to be Paid
90-100	100
80-90	0.5 PWL + 55.0
65-80	2.0 PWL - 65.0
Below 65	*

*The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu thereof, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall not be removed and will be paid for at 50 percent of the contract price.

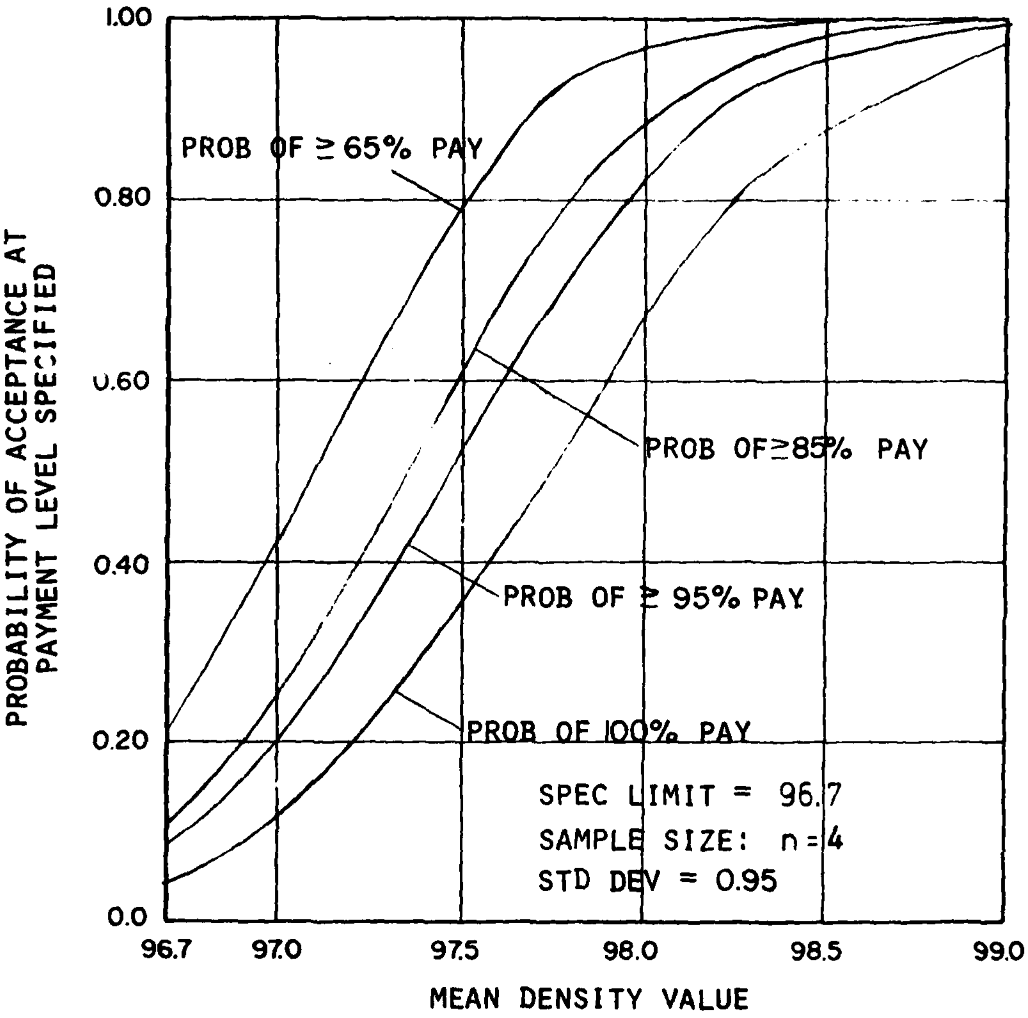


FIGURE 3.17 OPERATING CHARACTERISTICS FOR THE PROPOSED DENSITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 0.95 AND SAMPLE SIZE OF FOUR AND LOWER SPECIFICATION LIMIT OF 96.7

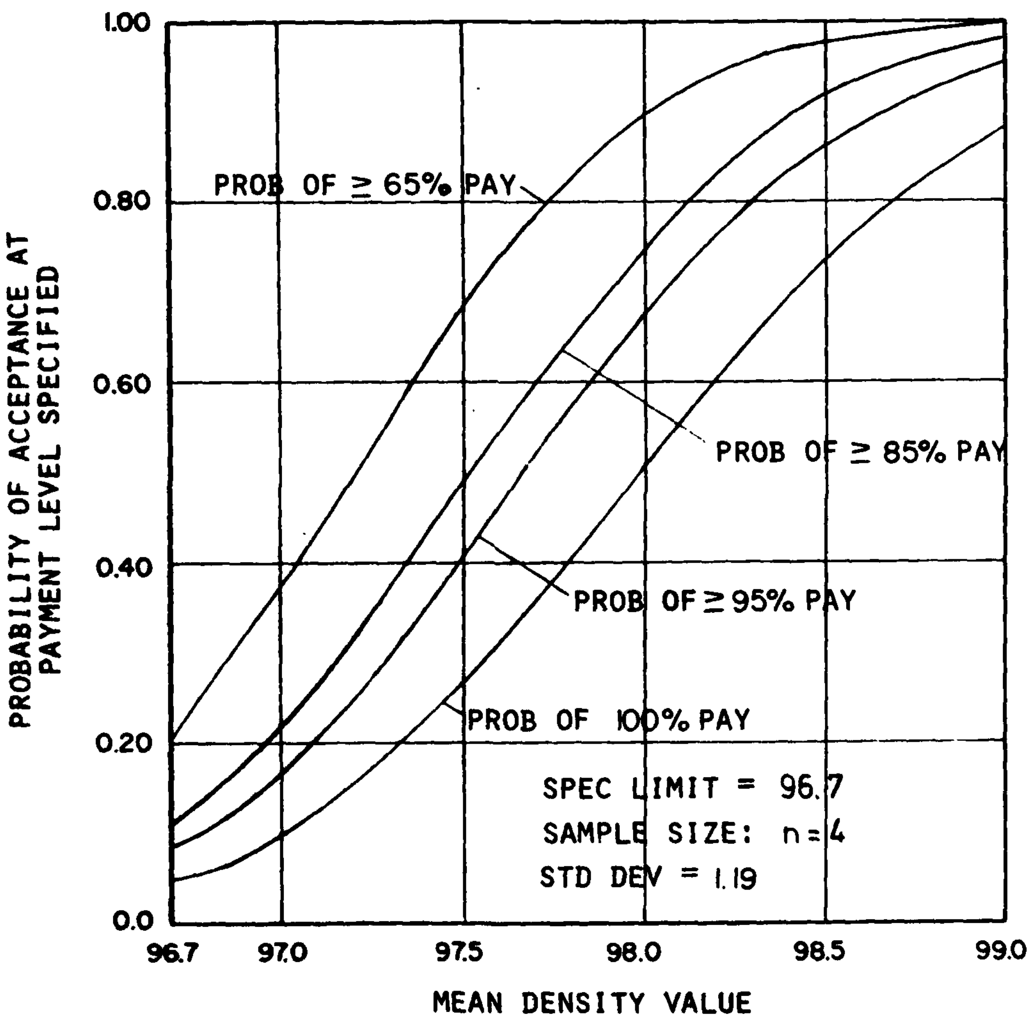


FIGURE 3.18 OPERATING CHARACTERISTICS FOR THE PROPOSED DENSITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 1.19 AND SAMPLE SIZE OF FOUR AND LOWER SPECIFICATION LIMIT OF 96.7

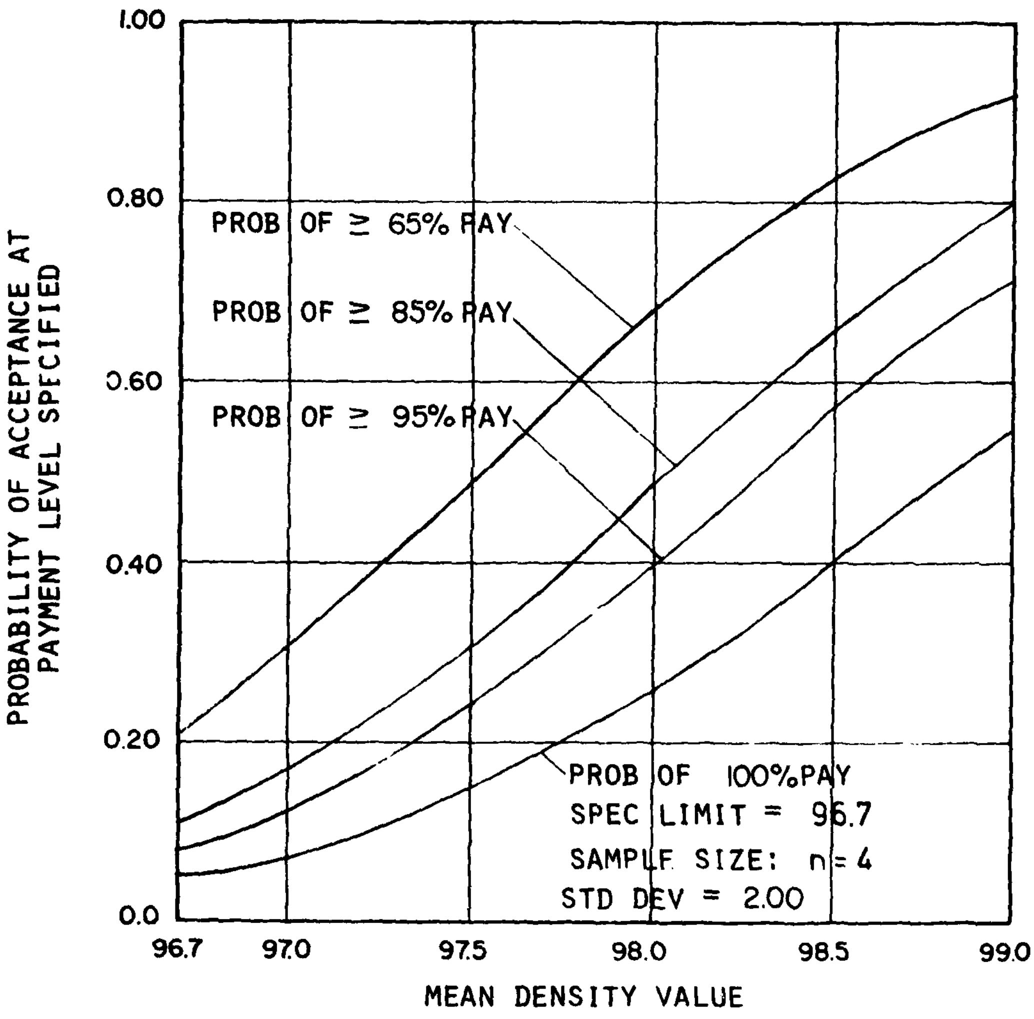


FIGURE 3.19 OPERATING CHARACTERISTICS FOR THE PROPOSED DENSITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 2.00 AND SAMPLE SIZE OF FOUR AND LOWER SPECIFICATION LIMIT OF 96.7

whereas 0.95 and 2.00 were chosen as indicative of better than average and below average values. The figures show curves for the probability of receiving 100 percent payment, the minimum payment of 65 percent, and intermediate payments of 95 percent and 85 percent. Figure 3.20 provides expected payment curves for the cases presented in Figures 3.17 through 3.19. These curves are based on the use of the payment schedule presented in Table 3.7.

Selection of Sample Size

The choice of the appropriate sample size is dictated, to a certain extent, by field considerations. If cores are used for acceptance, then the current sample size of four per lot, or perhaps five, is probably appropriate because of the time involved in taking and testing the cores and because coring is a destructive testing process. If nuclear devices are used for acceptance testing, then the speed and nondestructive nature of the testing process allows for larger sample sizes. In their discussions with contractors, consultants, and testing laboratories, the researchers detected some skepticism concerning the use of nuclear devices for acceptance purposes. There seemed to be much greater sentiment in favor of cores than of nuclear devices for acceptance testing. Because of the present sentiment among the contractors, it is believed that the use of cores should be retained as the primary method for density acceptance, but that the option of nuclear density measurements should also be retained. As nuclear devices become more accepted and trusted by the contractors and testing laboratories in general, the appropriate tables could be developed to allow for larger sample sizes, 10 or 20 for instance.

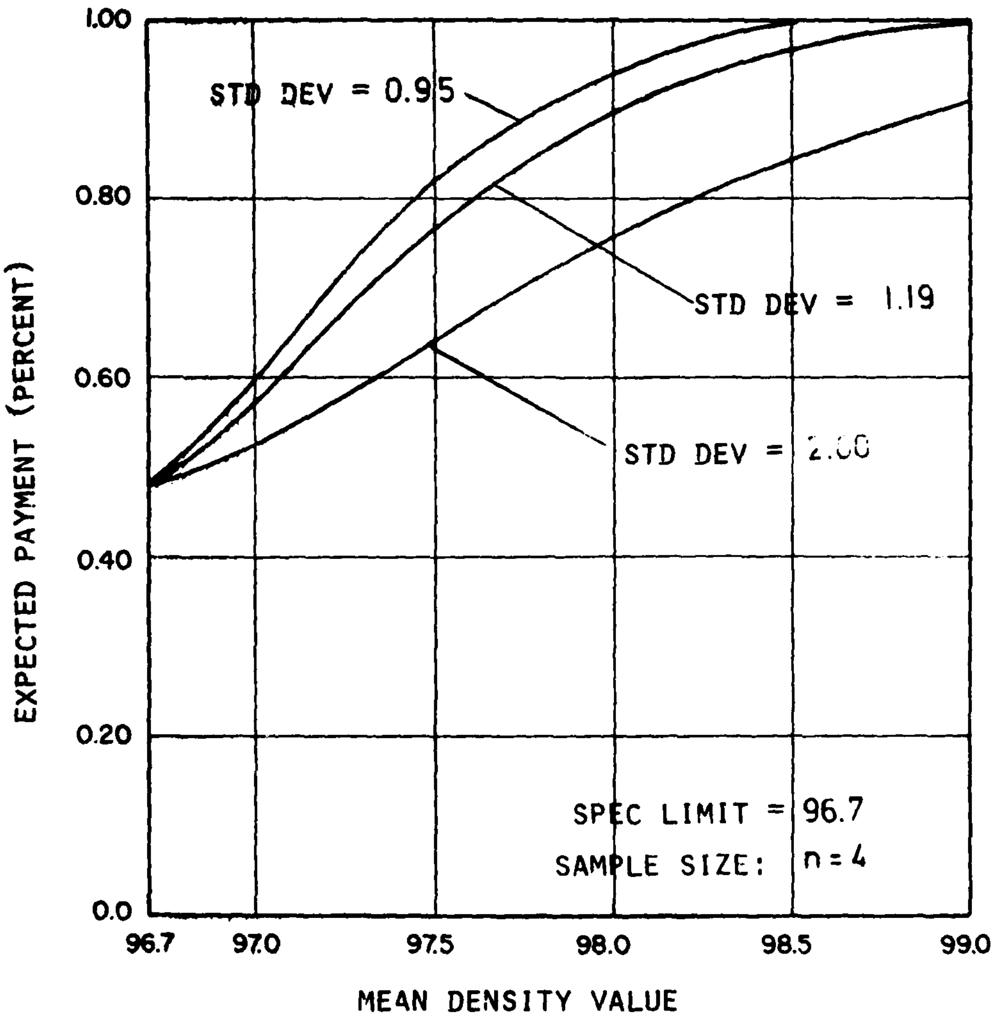


Figure 3.20 EXPECTED PAYMENT CURVES FOR THE PROPOSED DENSITY PAYMENT SCHEDULE II FOR A SAMPLE SIZE OF FOUR AND A LOWER SPECIFICATION LIMIT OF 96.7

SUMMARY AND RECOMMENDATIONS

A number of different topics relating to the FAA density acceptance plan have been presented and discussed in this chapter. Some of the recommendations which were made with regard to this plan are:

1) Use of the standard deviation method rather than the range method since the former provides a better estimate of PWL.
2) Use of a continuous price adjustment schedule to prevent major payment differences for small differences in the quality of the material. The recommended schedule is shown in Table 3.7 and Figure 3.7. This schedule was recommended on the basis of the close agreement of its expected payment curve with the expected payment curve of the price adjustment schedule originally proposed by the FAA.
3) Use of a computer simulation program to determine OC curves in terms of means and standard deviations which a contractor can easily relate to his construction process capabilities.

The recommended acceptance plan is summarized in Chapter 6, where its use is simulated on several projects from the 1978 construction season.

4. MARSHALL PROPERTIES

INTRODUCTION

This chapter presents the findings of the data analysis for the Marshall properties of stability, flow, and air voids. The development of proposed acceptance plans for these properties is also presented. In developing these plans, a computer simulation program was used to obtain the OC curves for those properties (flow and air voids) which had both upper and lower specification limits. Possible alternatives are presented for dealing with the case when more than one of these properties require price adjustments. Finally, the results of correlation tests among these three properties are presented.

ANALYSIS OF MARSHALL TEST RESULTS

The Marshall test results from each of the projects in the study were analyzed, and the mean and standard deviation were determined for each project. The results of this analysis are presented in Tables 4.1 through 4.3. There were a total of 532 Marshall tests conducted on the projects included in the study. Each Marshall test result is the average value of three specimens. The Marshall results from the Richmond project were not included in the analysis, because the Marshall results on this project were based on the average of four specimens per test rather than three, as was the case on all of the other projects. The FAA Eastern Region specifications require three specimens per test.

Tables 4.1 through 4.3 present, for each project, values for the number of tests, the job mix formula (JMF) values for stability, flow, and air voids, and the mean value and standard deviation for these parameters.

TABLE 4.1 RESULTS OF MARSHALL STABILITY TESTS FOR THE PROJECTS IN THE STUDY

Project	Number of Tests	JMF Value*	Mean Value	Offset from JMF	Standard Deviation
Adirondack - Type A	9	2200	2240.1	+ 40.1	288.51
Adirondack - Type B	29	2385	2341.6	- 43.4	256.46
Charlottesville - ANJ**	54	2300	2702.6	+ 402.6	271.32
Charlottesville - SLW	53	2410	3614.7	+1204.7	367.34
Chautauqua	27	2058	2450.4	+ 392.4	126.06
Chemung - Chemung	24	2260	2427.3	+ 167.3	156.15
Chemung - Fisherville	56	2929	2475.9	- 453.1	260.94
DuBois	32	2541	2056.1	- 484.9	173.49
Dutchess	12	2432	2835.6	+ 403.6	193.68
Linden	52	2171	2117.9	- 53.1	127.45
Westchester - Colprovia	99	2220	2816.1	+ 596.1	203.69
Westchester - Peckham	85	2640	2686.2	+ 46.2	436.86
TOTAL	532				
POOLED VALUES		2410	2642	+ 232	279

*Specification Range--Minimum of 1800 (pounds)
**Dryer Drum Plant

TABLE 4.2 RESULTS OF MARSHALL FLOW TESTS FOR THE PROJECTS IN THE STUDY

Project	Number of Tests	JMF Value*	Mean Value	*Offset from* JMF	*Standard* Deviation
Adirondack - Type A	9	10.0	10.15	+0.15	1.692
Adirondack - Type B	29	9.0	10.02	+1.02	1.445
Charlottesville - ANJ**	54	14.0	15.91	+1.91	1.349
Charlottesville - SLW	53	13.0	15.27	+2.27	2.800
Chautauqua	27	8.4	9.59	+1.19	0.799
Chemung - Chemung	24	10.9	10.39	-0.51	1.243
Chemung - Fisherville	56	9.5	9.05	-0.45	0.902
DuBois	32	9.6	10.44	+0.84	1.485
Dutchess	12	11.7	13.40	+1.70	1.325
Linden	52	13.0	11.90	-1.10	1.246
Westchester - Colprovia	99	14.0	11.41	-2.59	1.790
Westchester - Peckham	85	11.7	11.86	+0.16	2.540
TOTAL	532				
POOLED VALUES		11.88	11.87	-0.01	1.81

*Specification Range--8 to 16 (1/100 inches).
**Dryer Drum Plant

TABLE 4.3 RESULTS OF AIR VOIDS TESTS FOR THE PROJECTS IN THE STUDY

Project	Number of Tests	JMF Value*	Mean Value	Offset from JMF	Standard Deviation
Adirondack- Type A	9	3.7	3.43	-0.27	0.722
Adirondack - Type B	29	3.8	3.58	-0.22	0.623
Charlottesville - ANJ****	54	2.7***	2.68	-0.02	0.577
Charlottesville - SLW	53	4.1**	3.62	-0.48	0.964
Chautauqua	27	4.0	3.08	-0.92	0.310
Chemung - Chemung	24	4.1**	3.46	-0.64	0.293
Chemung - Fisherville	56	4.2**	3.68	-0.52	0.473
DuBois	32	3.9	3.58	-0.32	0.672
Dutchess	12	3.7	4.41	+0.71	0.410
Linden	52	3.9	3.86	-0.04	0.684
Westchester - Colprovia	99	3.5	3.69	+0.19	0.614
Westchester - Peckham	85	3.65	3.64	-0.01	1.179
TOTALS	532	3.72	3.55	-0.17	0.75

*Specification Range--2.7 to 4.7 (percent)
**The specification range on these projects was 3 to 5 (percent).
***The specification range on this project was 2 to 4 (percent).
****Dryer Drum Plant

The tables also present the pooled values of mean and standard deviation for all the test results. The mean offset from the JMF, as a measure of how well actual production coincided with the designed job mix, may be more meaningful than the actual mean values for stability, flow, and air voids.

Marshall Stability Results

The results of the analysis of the stability test values are included in Table 4.1. The mean value of stability from the JMF's on the project was 2410, whereas the actual mean value of the production stability tests was 2642. These numbers are both substantially higher than the minimum value of 1800 required by the FAA specifications, indicating that there was little difficulty encountered in meeting the stability requirement on the projects studied. The average offset from the JMF value for the projects studied was +232, but this number may be misleading. The offset on one project, Charlottesville-SLW, was 1204.7, whereas the offsets on the other projects ranged from +596.1 to -484.9. The average offset from the JMF value, if the Charlottesville-SLW project is omitted, was +125. The pooled standard deviation value for all the projects is 279. When this value is considered together with the high mean value of stability, it does not seem that the specification limit for stability is difficult to achieve.

Marshall Flow Results

The results of the analysis of the flow values are presented in Table 4.2. The mean value for the JMF flow values and the mean value for production tests are nearly identical, 11.88 versus 11.87. These mean values are both well within the FAA specification limits of 8 to 16. The average offset from the JMF value in essentially zero (-0.01), but this does not mean that the

JMF value is always obtained. The offset values on the individual projects varied from +2.27 to -2.59. The pooled standard deviation for the projects studied was 1.81. The mean production flow value of 11.87 is thus more than two standard deviations from the nearest specification limit. Upon initial analysis it appears that there are no major difficulties in meeting the FAA specification limits.

Air Voids Results

The results of the analysis of the air voids values are presented in Table 4.3. The mean JMF target value, 3.72, is a little misleading since one of the projects, Charlottesville-ANJ, had a specification range for air voids of 2 to 4 percent. The remainder of the projects used a range of either 3 to 5 percent (Charlottesville-SLW, Chemung-Chemung, Chemung-Fisherville) or 2.7 to 4.7 percent, which is the range specified in the FAA Eastern Region Specifications. If the mean JMF value and mean production value are determined for the projects bound by the specification range of 2.7 to 4.7 percent, then values of 3.71 and 3.65 are obtained. These values fall in the center of the 2.7 to 4.7 percent specification range.

The pooled value of standard deviation obtained for the projects was 0.75. This value is quite high in comparison with the specification range of 2.7 to 4.7 percent. A normal population, with a mean at the center of the specification range (3.7 percent) and with a standard deviation of 0.75, would have only about 82 percent of its area within the specification limits. This indicates that some problems may be encountered in meeting the specification requirements. It is possible either that the specification limits are too restrictive in light of the variability of the production process or that the estimated value of standard deviation is too high.

Upon investigation, it appears that some of the variability in the values for air voids may be attributed to the method by which the value for air voids content is determined. The method employed for calculating air voids is based upon a comparison of the actual specific gravity measured for the Marshall specimens after compaction versus the maximum theoretical specific gravity. The maximum theoretical specific gravity is dependent upon the specific gravities and the relative proportions of the aggregate and asphalt in the mix. On a number of the projects investigated, the maximum theoretical specific gravity was always based on the job mix formula (JMF) asphalt content. As will be seen when the asphalt extraction results are presented in Chapter 5, the asphalt content may vary from day to day. In the researchers' view, the asphalt content used for calculating maximum theoretical specific gravity should be based as nearly as possible on the actual asphalt content of the Marshall specimens being tested and not upon the JMF asphalt content.

An examination of the asphalt content test results indicates that the production asphalt content may vary by as much as 0.9 percent from the JMF design value. An example from one of the projects will help to illustrate how the asphalt content can influence the determination of air voids content. On the Linden project the JMF design asphalt content was 6.1 percent. This asphalt content yields a maximum theoretical specific gravity of 2.538. This value was used to calculate air voids content for each Marshall test throughout the project. The results of the extraction tests conducted on the project indicate values of asphalt content ranging from 6.99 to 5.72 percent. As an example (Figure 4.1), on November 24, 1978, two extraction tests yielded results of 6.14 and 6.99 for asphalt content. In the calculations for air

BITUMINOUS CONCRETE TESTING REPORT

PRODUCER: GALLO ASPHALT　　　DATE: 11/24/78

PROJECT: LINDEN AIRPORT　　　SPEC: P-401　SURFACE COURSE

COMPUTATION OF MARSHALL MIX PROPERTIES

SPECIMEN NO.	ASPHALT CONTENT PERCENT	THICKNESS INCHES	WGT. — GRAMS IN AIR	IN WATER	SAT. SURF. DRY	VOLUME cc	SP. GRAVITY ACT.	THEOR. Gmm	AC BY VOL %	VOIDS - % TOTAL MIX	FILLED VF	UNIT WGT. TOTAL MIX LB/CU. FT.	STABILITY - LB MEASURED	CONVERTED	FLOW UNITS OF 1/100 IN
A	B	C	D	E	E'	F	G	H	I	J	K	L	M	N	O
						(E'-E)	(D)/(F)		(BxG)/SP. GR. OF AC	(100-100×G/H)	I/(I+J)	(G x 62.4)			
SUBLOT NO. 1															
1-1	6.14	2½	1251.5	737.7	1253.0	513.1	2.437	2.538	14.68	3.9	79.01	152.17	2173	2173	13
1-2	6.14	2½	1248.8	737.7	1251.4	513.5	2.434	2.538	14.65	4.1	78.13	151.88	1781	1787	12
1-3	6.14	2½	1246.7	740.8	1247.7	509.1	2.447	2.538	14.74	3.5	80.81	152.82	2150	2150	13
AVG.			1247.3	737.5	1251.4	511.9	2.441		14.69	3.8	79.32	152.30	2103	2103	12.6
SUBLOT NO. 2															
2-1	6.99	2½	1253.4	737.5	1255.5	516.0	2.429	2.538	16.64	4.3	79.47	151.57	2113	2113	10
2-2	6.99	2½	1249.7	742.2	1251.0	508.8	2.454	2.538	16.82	3.3	83.67	153.13	2137	2137	13
2-3	6.99	2½	1248.6	[illegible]	1253.0	516.2	2.421	2.538	16.57	4.6	78.29	151.07	2163	2163	10
AVG.			1250.7	739.5	1253.2	513.7	2.435		16.68	4.1	80.45	151.92	2138	2138	11

NOTES:

CALCULATIONS BY: N. DILLON
AFFILIATION: ENVIROPLAN, INC

APPENDIX D Page 1

FIGURE 4.1 BITUMINOUS CONCRETE TEST REPORT FROM THE LINDEN PROJECT

voids content, even though the asphalt content was shown as 6.99 percent on the computation sheet, the value of 2.538, which corresponds to an asphalt content of 6.1 percent, was used as the maximum theoretical specific gravity. These calculations are shown in Figure 4.1. For this project, the value of maximum theoretical specific gravity that corresponds to an asphalt content of 6.99 percent is 2.503. If this value had been used in the calculation of air voids content, then values of 3.0, 2.0, and 3.3 percent would have been obtained rather than the values of 4.3, 3.3, and 4.6 shown in Figure 4.1.

It is true that the example cited is an extreme case and that the asphalt content will rarely vary this much from the JMF asphalt content. But even a variation of 0.2 or 0.3 percent from the JMF can cause significant changes in the calculated air voids content. For the example, in Figure 4.1, if the asphalt content had been 6.4 percent (0.3 percent from the JMF value of 6.1), then the maximum theoretical specific gravity would have been 2.527, and values of 3.9, 2.9, and 4.2 percent would have been obtained. These values are 0.4 percent lower than the values obtained in Figure 4.1. When one considers that the specification range, 2.7 to 4.7, spans only 2.0 percent, a difference of 0.4 percent can be significant.

It has been shown that the value for air voids content can be changed rather dramatically if variations in asphalt content are not taken into account by modifying the maximum theoretical specific gravity. It is therefore recommended that the maximum theoretical specific gravity used in the determination of air voids content be adjusted to reflect the asphalt content of the material being produced. On plants with automatic recordation, an

estimate of the asphalt content for the batch from which the Marshall specimens are taken can be obtained from the values on the printed batch tickets. In other cases, the asphalt content from the most recent extraction test could be used to determine maximum theoretical specific gravity. Ideally, an extraction test could be run on one of the tested Marshall specimens, and this value could then be used for calculating air voids content.

DEVELOPMENT OF ACCEPTANCE PLAN

The results of the data analysis phase for Marshall properties were used to develop acceptance plans for these properties. For Marshall stability the analysis is similar to that for density since there is only a lower limit specified. For Marshall flow and for air voids, which have both upper and lower specification limits, a purely theoretical approach becomes difficult. For these properties a computer simulation program was developed to determine the operating characteristics of the proposed acceptance plans. This was done because it is possible for material to be outside both specification limits at the same time.

The approach used to obtain these proposed plans is based on the development of the OC curves and expected payment curves for each of the properties on the basis of the payment schedule for density originally developed by FAA. The final determination of the reasonableness or appropriateness of any of the plans presented can only be made by the FAA.

Continuous Versus Discrete Price Adjustments

In Chapter 3 it was argued that a continuous price adjustment schedule is preferable to a discrete schedule, and therefore a continuous schedule was developed and recommended for the case of density. Discrete price adjustment schedules are proposed for the Marshall properties because the calculations

are considerably simplified in this way. In Chapter 3, it was shown that the expected payment curve for the continuous schedule is very similar to the discrete schedule on which it was based. It is likely that the expected payment curves for the Marshall properties would be very close to those for the proposed discrete schedules.

It is recommended that, at this time, the discrete schedules presented in this chapter be maintained for the Marshall properties. Dealing with multiple price adjustments for the Marshall properties will make the initial field applications much more complicated than was the case for density, where only one property was involved. It is therefore recommended that the discrete schedules be employed for the first construction season, since the parties involved--contractors, consultants, and testing laboratories--are already familiar with this type of schedule from the density specification used during the last construction season. If the continuous price adjustment schedule for density were used during the next construction season, then all parties involved would have an opportunity to become familiar with this approach, and it could then be adopted for Marshall properties during later construction seasons.

Computer Simulation Program

The operating characteristics for properties with both upper and lower specification limits were determined by means of a computer simulation program. This is necessary since there are many ways in which a particular value for PWL could be obtained from a population having a given standard deviation. For example, a population with a given standard deviation could have a PWL value of 80 by having a mean value for which 10 percent was below the lower limit and 10 percent was above the upper limit, or for which 20 percent was below the lower limit and nothing above the upper limit.

This example is oversimplified, but it helps to illustrate some of the potential difficulties with the analysis for two specification limits.

The simulation program is similar to that used by Willenbrock and Kopac (9), but it was modified to use the standard deviation method rather than the range method for estimating PWL. The program was originally written by Charles E. Antle of the Department of Statistics of The Pennsylvania State University.

The program determines the operating characteristics of the proposed acceptance plan by simulating the random sampling of 10,000 lots of material. The mean and standard deviation for the population being considered are entered into the program. The number of samples per lot is a variable which can be entered into the program. For the OC curve development for the Marshall properties, a sample size of four was used since this is the value required by the Eastern Region specifications. A copy of the program, together with a more thorough discussion, is presented in Appendix A.

In order to test the simulation program, it was used to determine the OC curves for the density acceptance plan. Since the program is set up for both an upper and lower specification limit, and density has only a lower specification limit, a very high value that was certain never to be exceeded was entered as the upper limit. The OC curves derived from this simulation are presented in Figure 4.2. The operating characteristics derived from the simulation were compared with those obtained from the theoretical solution using the non-central t-distribution presented in Figure 3.11. As can be seen from Table 4.4, the results agree quite closely, thus verifying the applicability of the program.

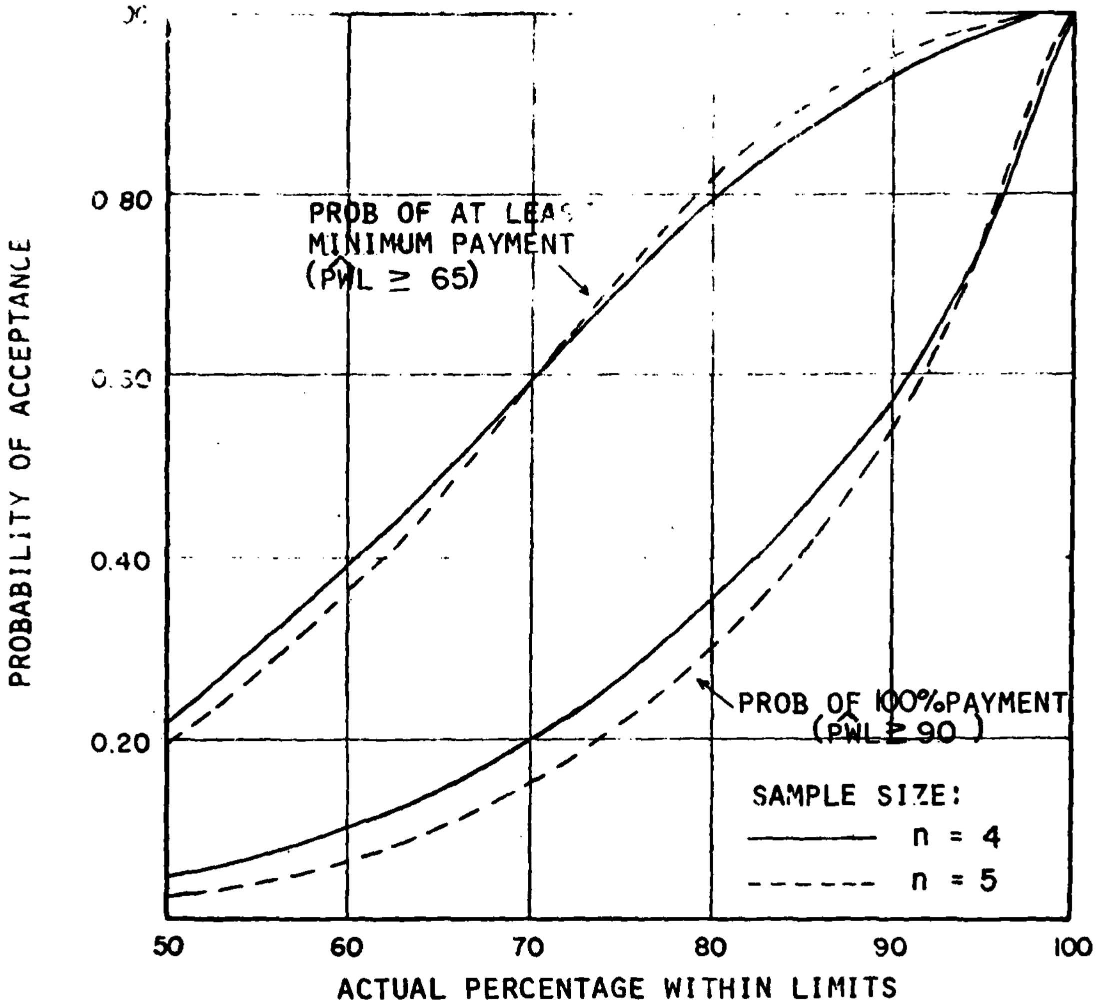


FIGURE 4.2 OPERATING CHARACTERISTICS CURVES FOR THE PROPOSED DENSITY ACCEPTANCE PLAN AS DETERMINED BY COMPUTER SIMULATION PROGRAM

TABLE 4.4 COMPARISON OF SIMULATION PROGRAM RESULTS FOR DENSITY WITH RESULTS OBTAINED THEORETICALLY BY USE OF THE NON-CENTRAL t-DISTRIBUTION FOR A STANDARD DEVIATION OF 1.23

Sample Size, n=4

Actual PWL	Simulation $\bar{X}$	Probability of $\hat{PWL} \geq 90$		Probability of $\hat{PWL} \geq 85$		Probability of $\hat{PWL} \geq 80$		Probability of $\hat{PWL} \geq 75$		Probability of $\hat{PWL} \geq 70$		Probability of $\hat{PWL} \geq 65$	
		Theoretical*	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation
50	96.700	4.8	4.8	6.3	6.2	8.5	8.4	11.5	11.5	15.8	15.4	21.7	21.5
60	97.012	10.3	10.1	13.3	13.0	17.3	17.0	22.6	22.4	29.5	29.5	38.1	39.0
70	97.345	20.0	19.9	25.0	24.9	31.3	31.2	39.0	39.6	48.2	49.0	58.3	59.7
80	97.735	35.8	36.1	43.1	43.6	51.4	52.4	60.7	61.9	70.1	71.0	79.0	79.8
90	98.276	61.1	61.8	69.2	70.2	77.3	78.2	84.6	85.0	90.6	90.8	94.9	95.1
98	99.226	91.4	91.3	95.0	95.0	97.5	97.8	99.0	99.2	99.6	99.7	99.9	99.9

Sample Size, n=5

Actual PWL	Simulation $\bar{X}$	Probability of $\hat{PWL} \geq 90$		Probability of $\hat{PWL} \geq 85$		Probability of $\hat{PWL} \geq 80$		Probability of $\hat{PWL} \geq 75$		Probability of $\hat{PWL} \geq 70$		Probability of $\hat{PWL} \geq 65$	
		Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation	Theoretical	Simulation
50	96.700	2.6	2.6	4.0	4.0	6.0	6.0	9.1	9.1	13.5	13.6	19.8	19.7
60	97.012	6.7	6.4	9.9	10.0	14.3	14.1	20.3	20.1	28.1	27.3	37.8	37.2
70	97.345	15.1	14.9	21.3	20.6	29.0	28.0	38.4	37.1	49.1	48.7	60.5	59.6
80	97.735	31.0	30.3	40.8	40.5	51.6	51.1	62.7	61.8	73.5	73.2	82.6	82.0
90	98.276	59.0	58.7	70.3	69.7	80.2	80.0	88.0	87.9	93.6	93.7	96.9	96.9
98	99.226	92.5	92.3	96.6	96.6	98.7	98.6	99.6	99.5	99.9	99.9	100.0	100.0

*These values can be obtained from Table 3.3. The probability of $\hat{PWL} \geq 90$ corresponds to the probability of receiving 100 percent payment in Table 3.3. The probability of $\hat{PWL} \geq 85$ corresponds to the sum of the probability of receiving 100 percent and 98 percent payment, and so on. For example, the probability of $\hat{PWL} \geq 80$ for an actual PWL value of 50 is the sum of the probability of receiving 100, 98, or 95 percent payment from Table 3.3 (4.8 + 1.5 + 2.2 = 8.5).

Marshall Stability

The case of Marshall stability is similar to that of density since there is only a lower specification limit involved. For this case, the operating characteristics can be determined theoretically by use of the non-central t-distribution. As a starting point for a Marshall stability acceptance plan, the FAA price adjustment schedule for density was used. This schedule was used because a subjective analysis is necessary for the OC curve method which was being employed for the development of the acceptance plan, and because FAA considered this schedule reasonable when they adopted it.

Since the same price adjustment schedule was used, the OC curves for Marshall stability are identical to those presented in Figure 3.2 for the FAA density acceptance plan. The OC curves for the proposed Marshall stability acceptance plan are presented in Figure 4.3. The OC curves for Marshall stability also were determined by use of the computer simulation program discussed above. As indicated in Chapter 3, the simulation allows the OC curves to be presented in terms of means and standard deviation values which the contractor can relate to his construction process capabilities. Since stability has only a lower specification limit (1800), an upper specification limit of 9000 was used in the program. The OC curves for the stability acceptance plan are presented in Figures 4.4 through 4.6. These figures are for standard deviation values of 175, 279, and 425, respectively. The value of 279 corresponds to the pooled standard deviation for all of the projects studied; 175 and 425 correspond to above average and below average control respectively, as indicated by the individual project results in Table 4.1.

In order to evaluate the acceptance plan, the expected payment curves for the OC curves shown in Figures 4.4 through 4.6 were determined. These expected payment curves are presented in Figure 4.7, and sample calculations

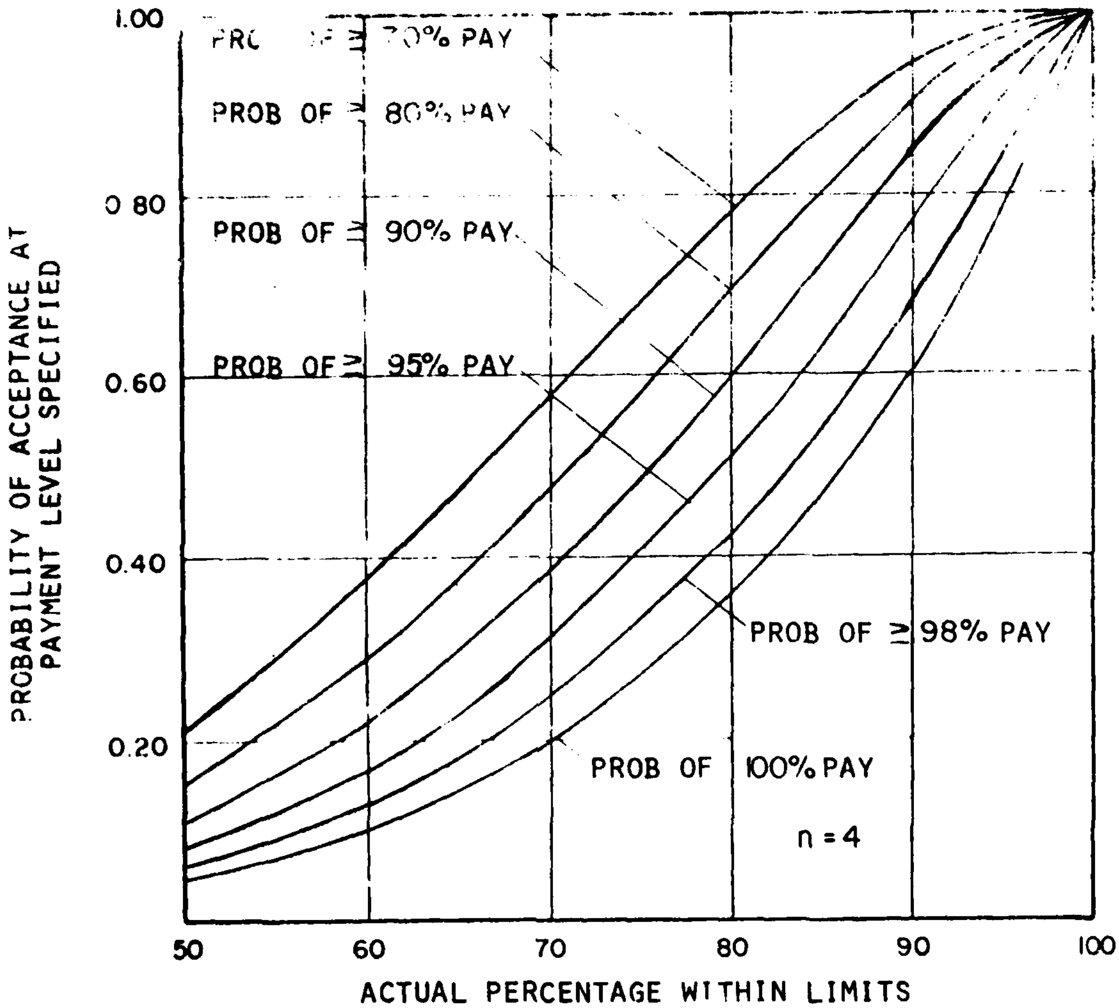


FIGURE 4.3 SET OF OPERATING CHARACTERISTICS CURVES FOR THE PROPOSED MARSHALL STABILITY ACCEPTANCE PLAN

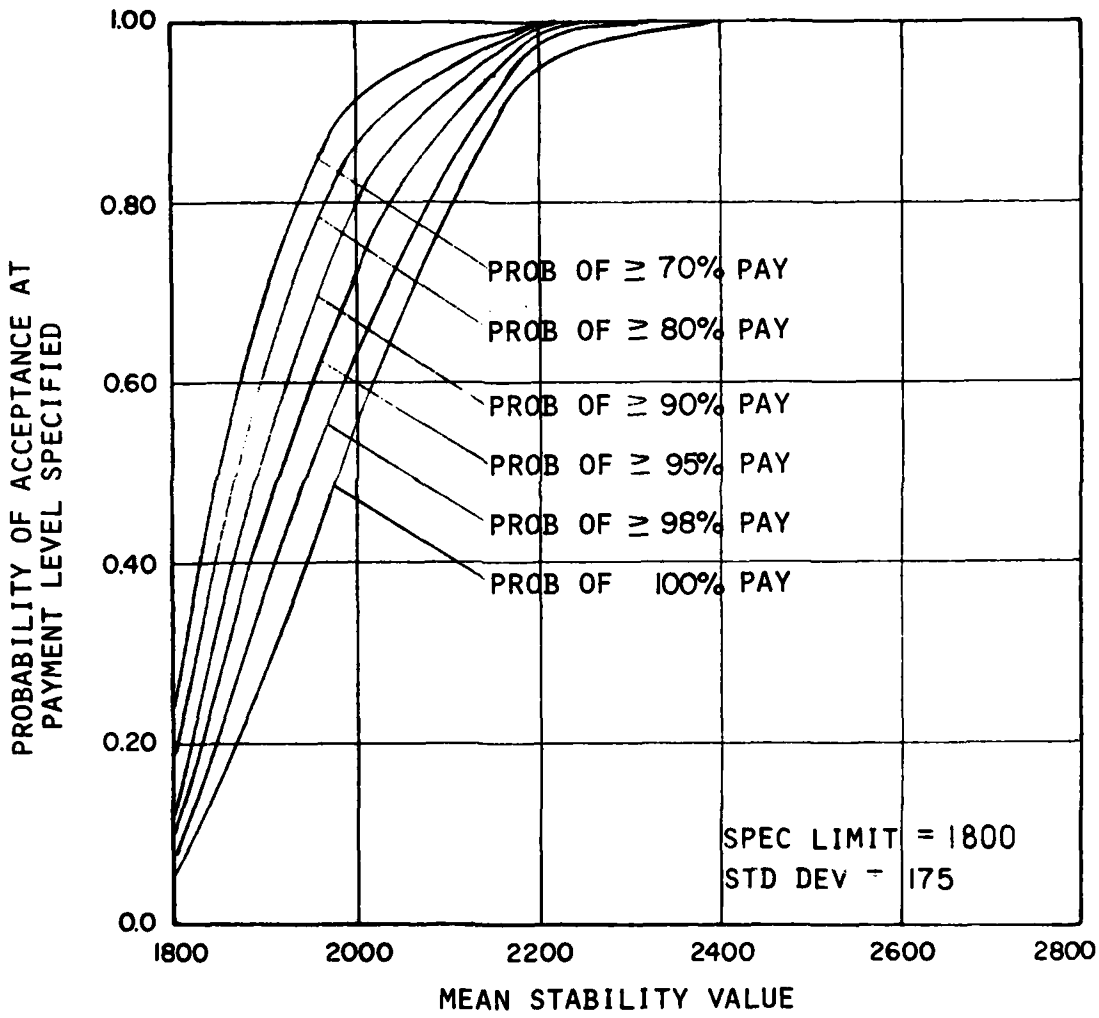


FIGURE 4.4 OPERATING CHARACTERISTICS FOR THE PROPOSED STABILITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 175

AD-A080 430 PENNSYLVANIA TRANSPORTATION INST UNIVERSITY PARK F/G 1/5
ACCEPTANCE CRITERIA FOR BITUMINOUS SURFACE COURSE ON CIVIL AIRP--ETC(U)
OCT 79 J L BURATI, J H WILLENBROCK DOT-FA78WA-4185
UNCLASSIFIED PTI-7915 FAA-RD-79-89 NL

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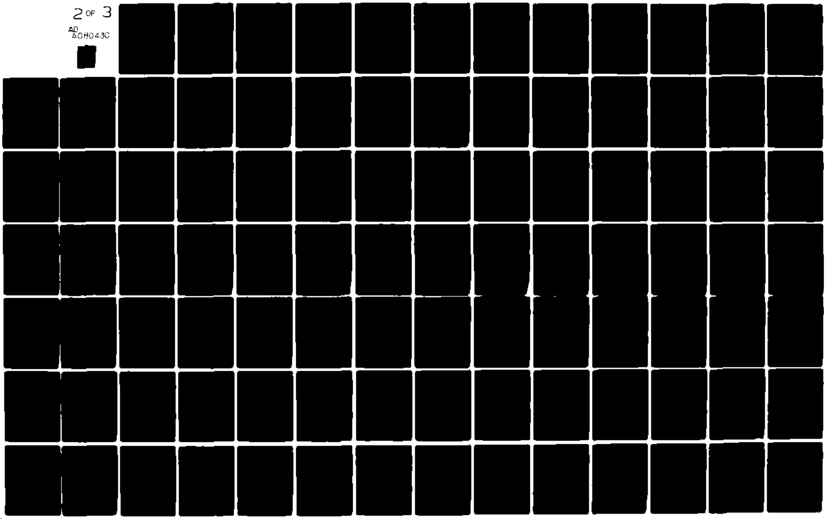

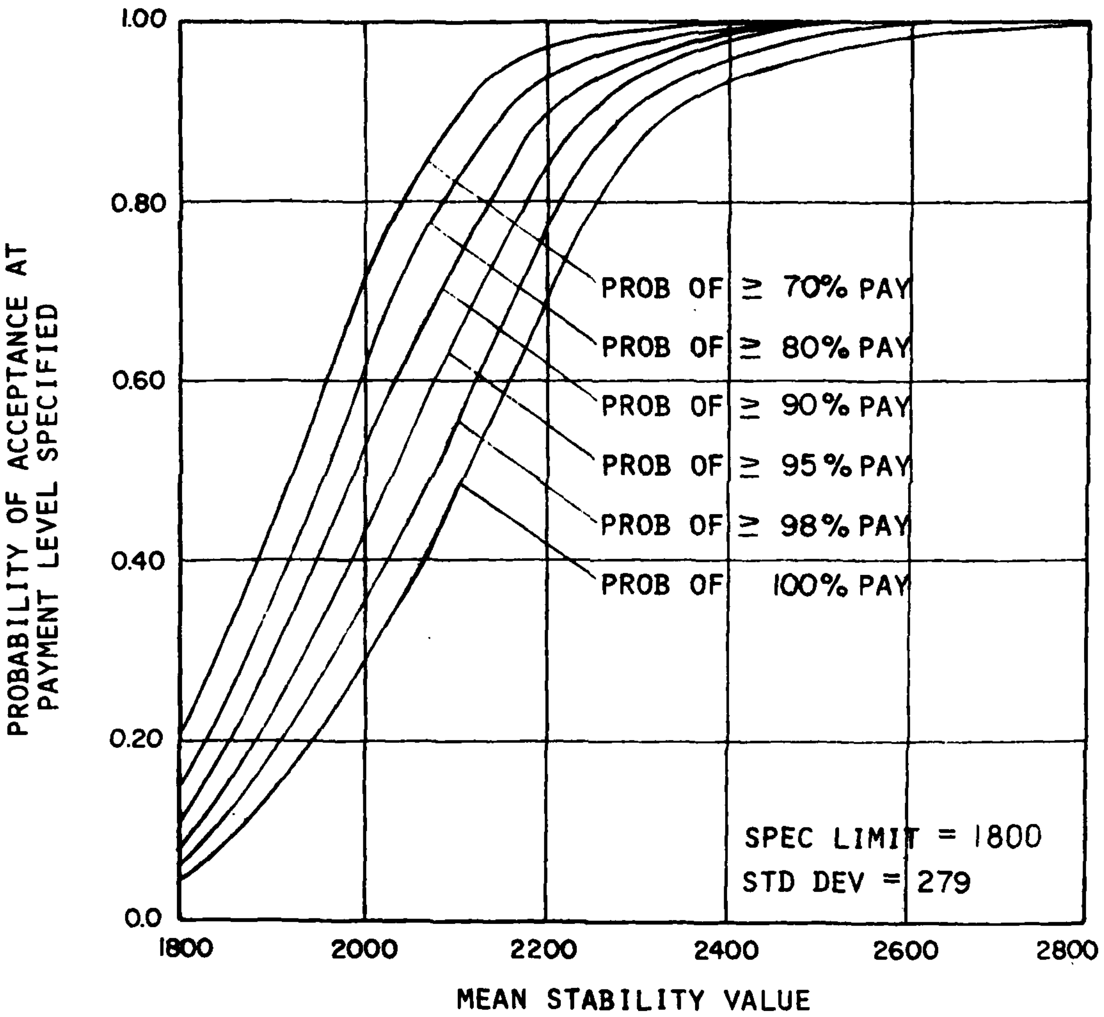

FIGURE 4.5 OPERATING CHARACTERISTICS FOR THE PROPOSED STABILITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 279

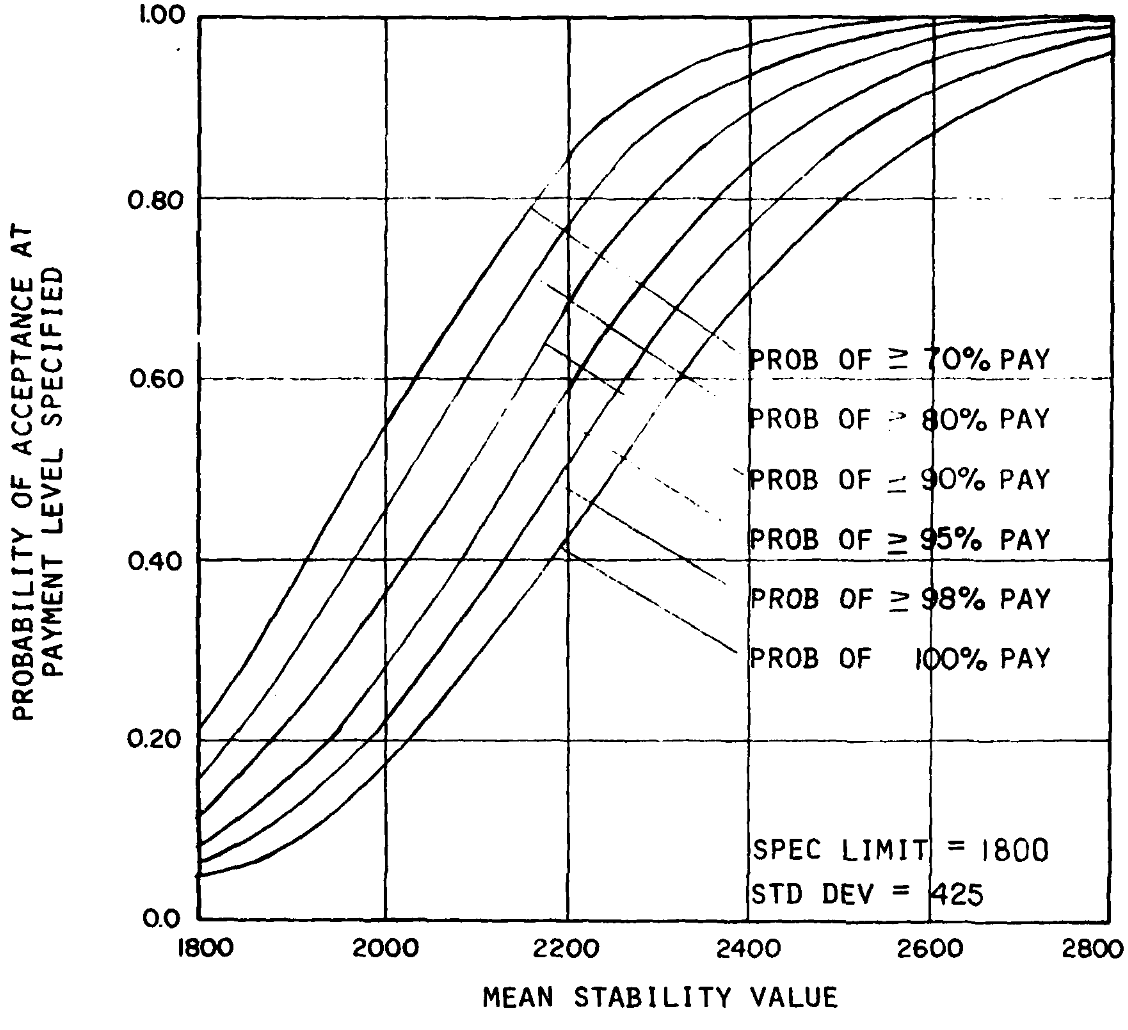

FIGURE 4.6 OPERATING CHARACTERISTICS FOR THE PROPOSED STABILITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 425

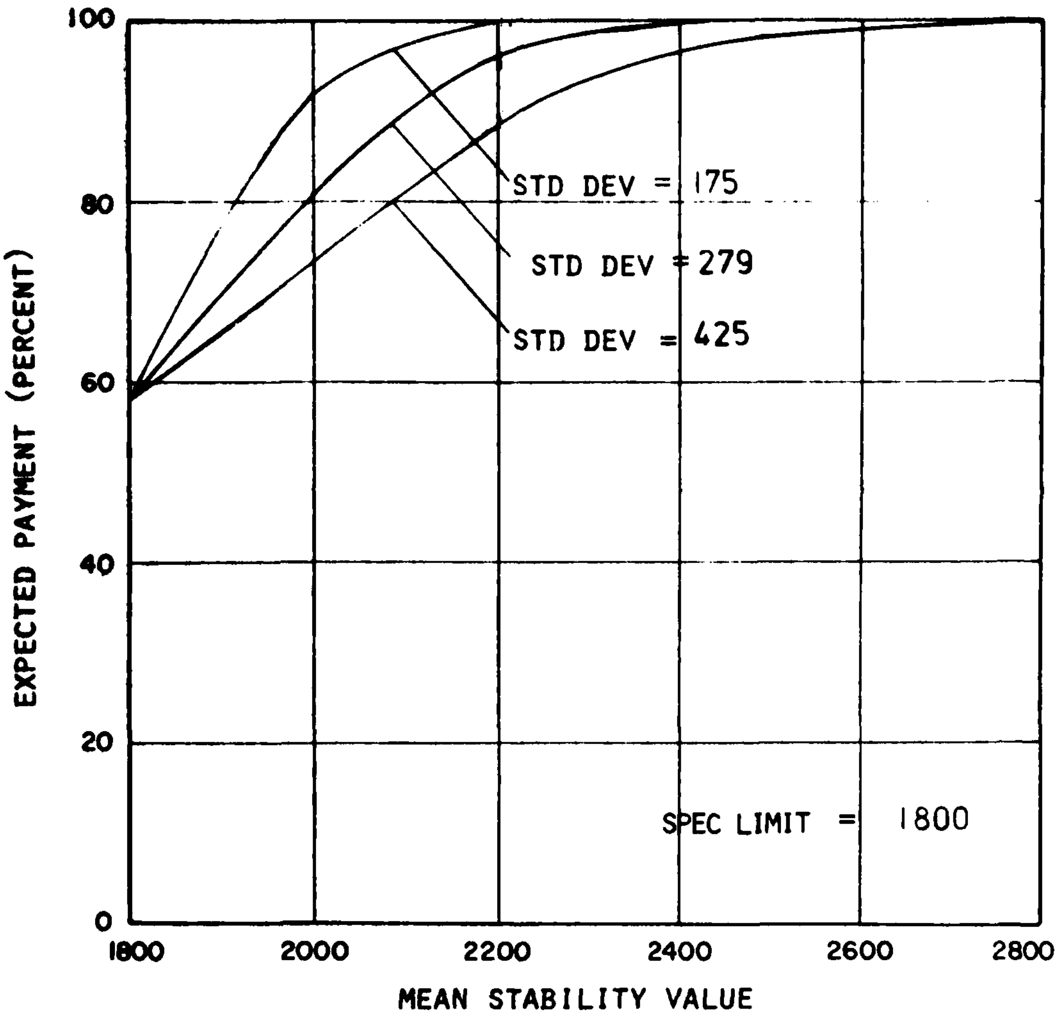

FIGURE 4.7 EXPECTED PAYMENT CURVE FOR THE PROPOSED STABILITY ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 175, 279 AND 425

necessary to develop the curve for a standard deviation of 279 are shown in Table 4.5. The curve associated with a standard deviation of 279 is probably the most representative of the value attainable in the field since it corresponds to the pooled standard deviation obtained from all of the projects studied. As can be seen from the curve, a contractor producing material at a mean stability value of 2410, which was obtained in the study, will have an expected payment of 100 percent. This curve seems to indicate that the proposed stability acceptance plan and price adjustment schedule are reasonable. The price adjustment schedule is presented in Table 4.6. It should be noted that in arriving at the expected payment curves shown in Figure 4.7, it was assumed that all material with an estimated PWL below 65 would be accepted at 50 percent payment. This was believed to be reasonable since it seems unlikely that removal would be ordered if only one of the three Marshall properties were below 65 PWL.

Marshall Flow

The case of an acceptance plan for Marshall flow is somewhat different from that for density or stability since there are both upper and lower specification limits involved. The FAA density price adjustment schedule, which had been used for the proposed stability acceptance plan, was also used for flow. This schedule was deemed appropriate because it is based on PWL, and PWL can be determined for either an upper or a lower specification limit.

The procedure for determining the estimated PWL for the case of a two-sided specification limit is similar to the method described earlier (Chapter 3) for the case of only a lower limit. For the two-sided case,

TABLE 4.5 CALCULATIONS FOR THE EXPECTED PAYMENT CURVE FOR THE PROPOSED MARSHALL STABILITY PRICE ADJUSTMENT SCHEDULE FOR A STANDARD DEVIATION OF 279 AND SPECIFICATION LIMIT OF 1800 POUNDS

Mean Value	Probability of Receiving Indicated Payment							Expected Value
	100	98	95	90	80	70	50	
1800	.048	.014	.022	.031	.039	.061	.785	57.7
2000	.288	.070	.082	.093	.100	.091	.276	80.0
2200	.700	.077	.066	.058	.044	.029	.026	95.9
2400	.933	.031	.022	.009	.003	.001	.001	99.6
2600	.993	.005	.001	.001	--	--	--	100.0
2800	.999	.001	--	--	--	--	--	100.0

TABLE 4.6 PRICE ADJUSTMENT SCHEDULE FOR THE PROPOSED MARSHALL STABILITY AND FLOW ACCEPTANCE PLANS

Estimated PWL	Percent of Contract Price to be Paid
90 and above	100
85 to 90	98
80 to 85	95
75 to 80	90
70 to 75	80
65 to 70	70
Below 65	*

*The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu thereof, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall be removed and will be paid for at 50 percent of the contract unit price.

two Quality Index values, Q_U and Q_L, must be determined from the following:

$$Q_U = \frac{U-\bar{X}}{S}$$

and

$$Q_L = \frac{\bar{X}-L}{S}$$

where: $\bar{X}$ = mean of the measurements on the lot

U = specification upper tolerance limit

L = specification lower tolerance limit

S = standard deviation of the measurements on the lot.

Once the calculations have been completed, the value of Q_U can be used together with Table 3.5 to determine the estimated percentage of material below the upper limit (PWL_U). Similarly, the value of Q_L can be used to estimate the percentage of the material above the lower limit (PWL_L). The PWL estimate for the lot can then be determined from the following relationship:

$$PWL = PWL_U + PWL_L - 100.$$

For the case of Marshall flow, the upper specification limit is 16 and the lower specification limit is 8. The OC curves for the proposed price adjustment schedule were determined by use of the computer simulation program discussed above and in Appendix A.

The OC curves corresponding to standard deviation values of 0.90, 1.25, 1.81, and 2.50 are shown in Figures 4.8 through 4.11. These values correspond to the lowest value, a lower than average value, the pooled value for all projects, and a higher than average value for standard deviation shown in

Table 4.2. As can be seen in Figure 4.8, a process that maintains a standard deviation of 0.90 has little or no chance of having material rejected when its mean value is between 10 and 14.

To evaluate the acceptance plan, the expected payment curves were determined for the OC curves shown in Figures 4.8 through 4.11, and are presented in Figure 4.12. Sample calculations necessary to develop the curve for a standard deviation of 1.81 are shown in Table 4.7. To arrive at these curves, it was again assumed that the material with an estimated PWL of less than 65 would be accepted at 50 percent payment 100 percent of the time. The curve associated with a standard deviation of 1.81 is probably the most representative of the value attainable in the field, since it corresponds to the pooled standard deviation obtained from all the projects studied.

Air Voids

The case of an acceptance plan for air voids content is similar to that for Marshall flow since there are both upper and lower specification limits. The calculations necessary to estimate PWL for the case of air voids are similar to those described for Marshall flow except that the lower specification limit is 2.7 percent and the upper specification limit is 4.7 percent. The high value obtained for the pooled standard deviation for air voids on the projects studied presented some problems in developing an acceptance plan and a price adjustment schedule. The same price adjustment schedule used for Marshall stability and flow was used for air voids. The OC curves corresponding to this schedule and the pooled standard deviation value for air voids of 0.75 are presented in Figure 4.13. As can be seen from this figure, the probabilities of acceptance, even for values in the center of

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (12 in this case). That is, the values obtained for a mean flow value of 13 are the same as for a value of 11, etc.

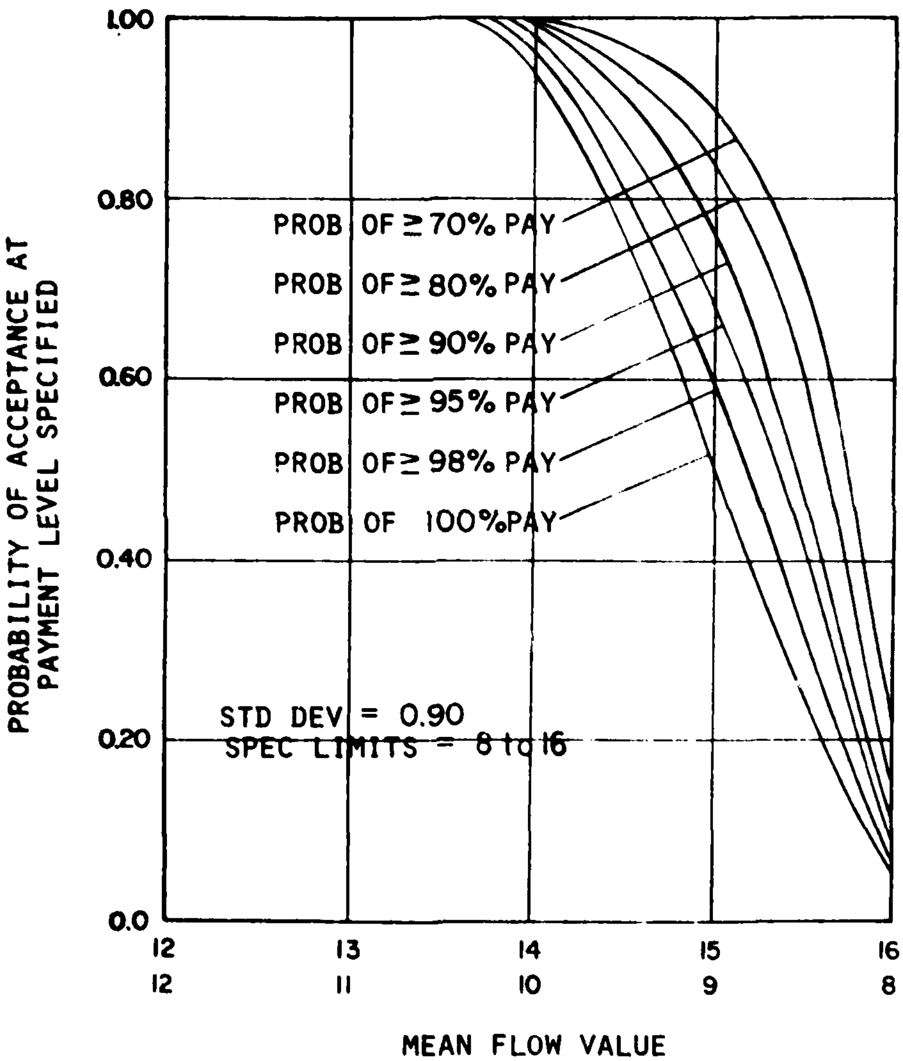

FIGURE 4.8 OPERATING CHARACTERISTICS FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 0.90

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (12 in this case). That is, the values obtained for a mean flow value of 13 are the same as for a value of 11, etc.

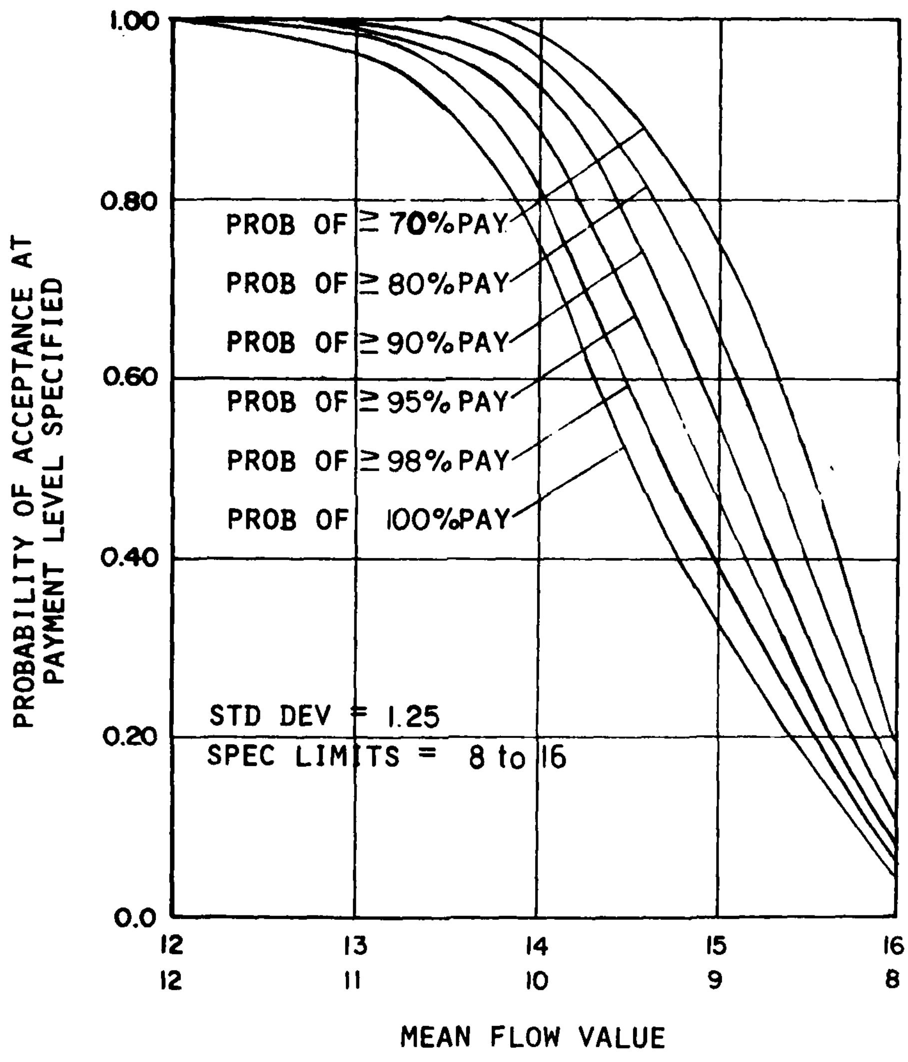

FIGURE 4.9 OPERATING CHARACTERISTICS FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 1.25

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (12 in this case). That is, the values obtained for a mean flow value of 13 are the same as for a value of 11, etc.

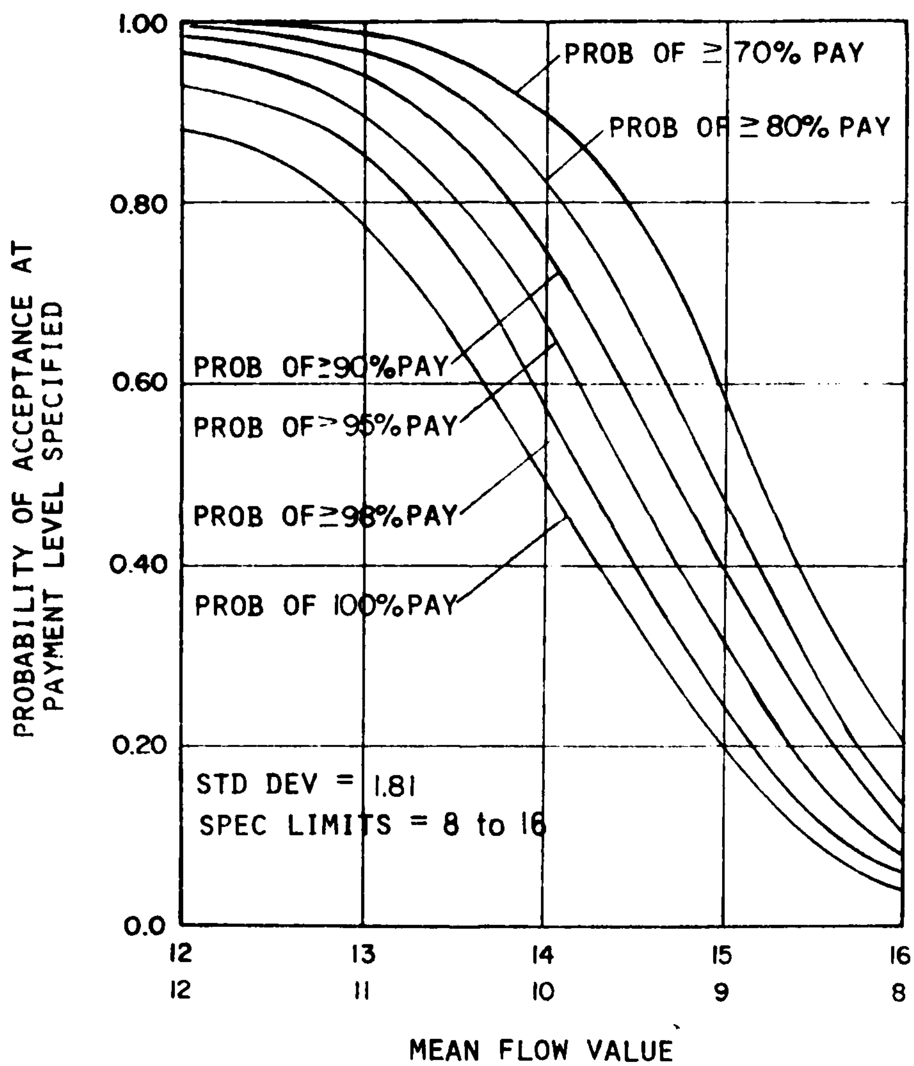

FIGURE 4.10 OPERATING CHARACTERISTICS FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 1.81

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (12 in this case). That is, the values obtained for a mean flow value of 13 are the same as for a value of 11, etc.

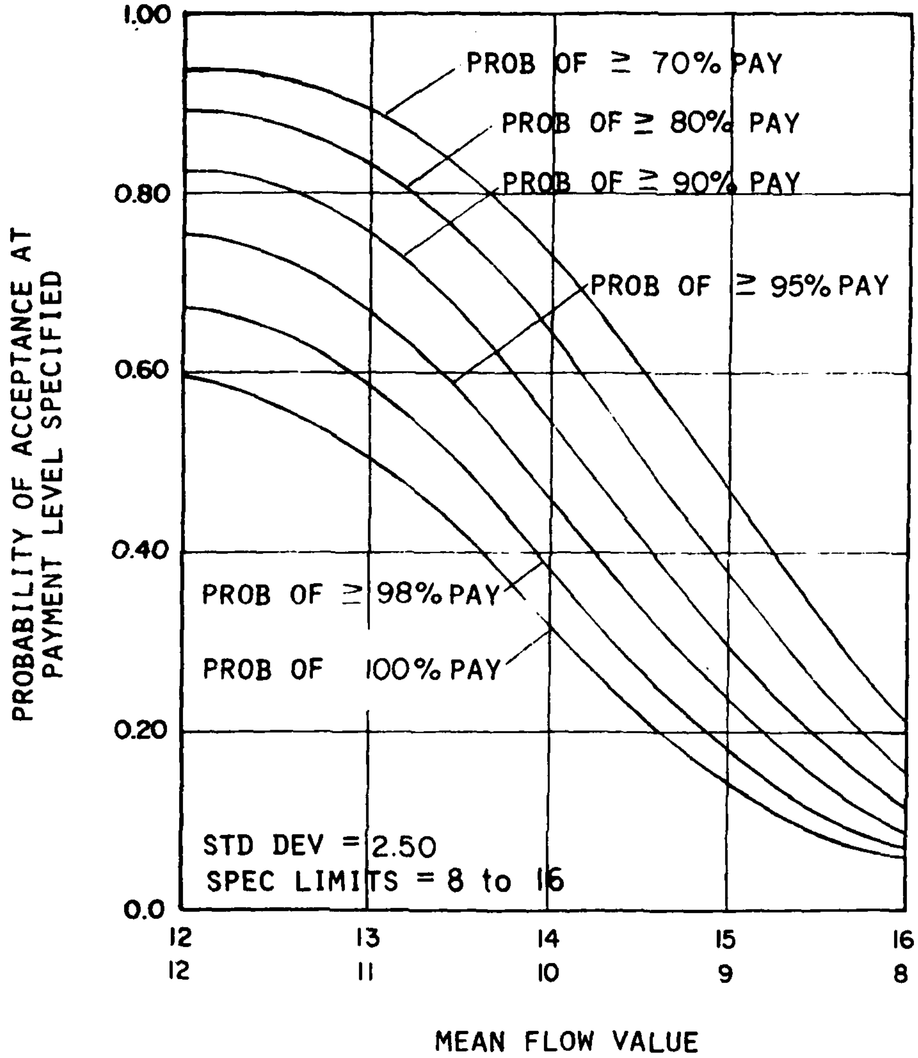

FIGURE 4.11 OPERATING CHARACTERISTICS FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 2.50

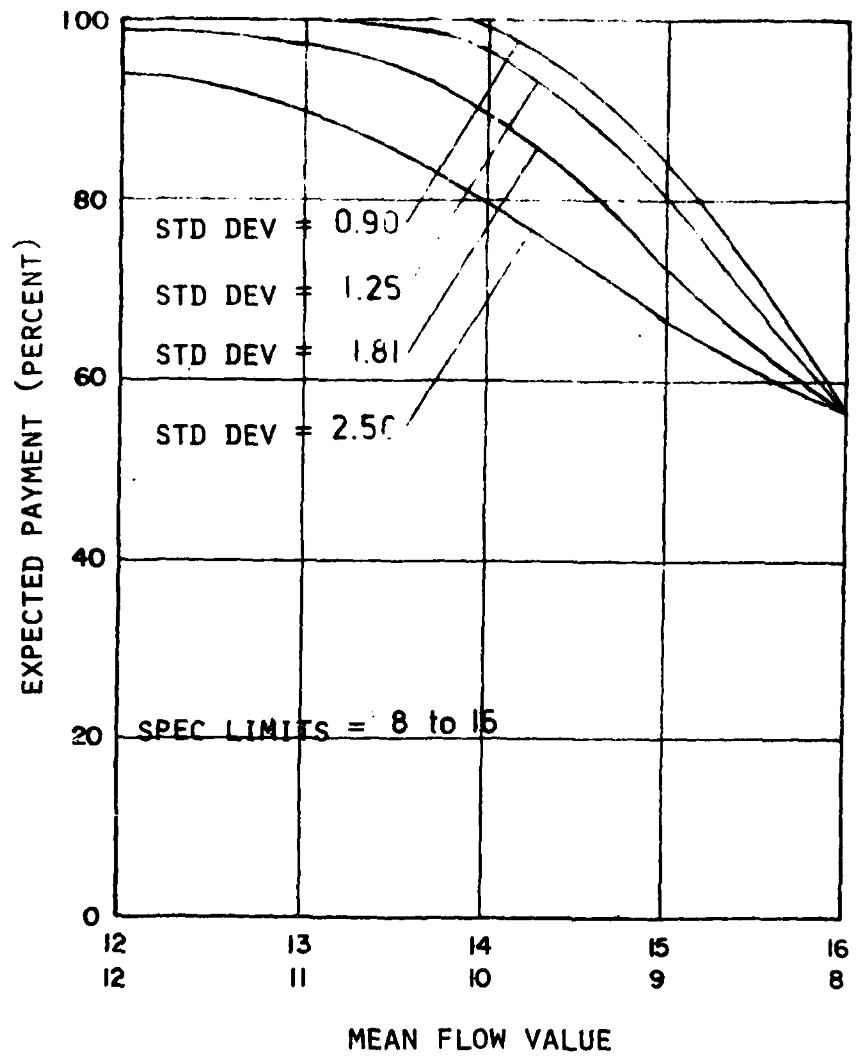

Figure 4.12 EXPECTED PAYMENT CURVES FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR STANDARD DEVIATIONS OF 0.90, 1.25, 1.81, AND 2.50

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (12 in this case). That is, the values obtained for a mean flow value of 13 are the same as for a value of 11, etc.

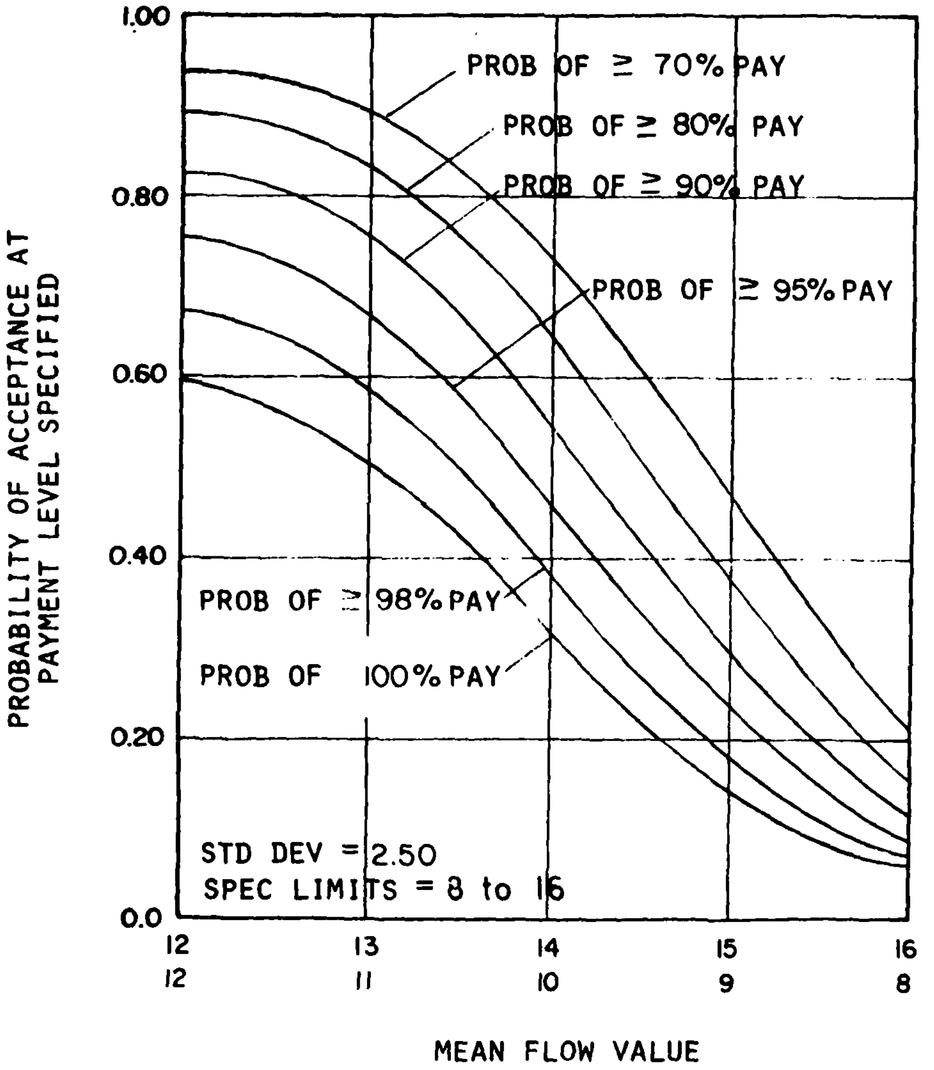

FIGURE 4.11 OPERATING CHARACTERISTICS FOR THE PROPOSED MARSHALL FLOW ACCEPTANCE PLAN FOR A STANDARD DEVIATION OF 2.50

TABLE 4.7 CALCULATIONS FOR THE EXPECTED PAYMENT CURVE FOR THE PROPOSED PRICE ADJUSTMENT SCHEDULE FOR MARSHALL FLOW FOR A STANDARD DEVIATION OF 1.81 AND SPECIFICATION LIMITS OF 8 TO 16

Mean Value	Probability of Receiving Indicated Payment							Expected Payment
	100	98	95	90	80	70	50	
12	.882	.048	.035	.017	.011	.005	.002	99.1
13 (11)	.782	.065	.054	.044	.028	.017	.010	97.6
14 (10)	.504	.087	.087	.081	.076	.067	.098	90.2
15 (9)	.210	.053	.063	.078	.089	.105	.402	73.8
16 (8)	.047	.014	.019	.030	.041	.064	.785	57.6

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content of 3.9 are the same as for 3.5, etc.

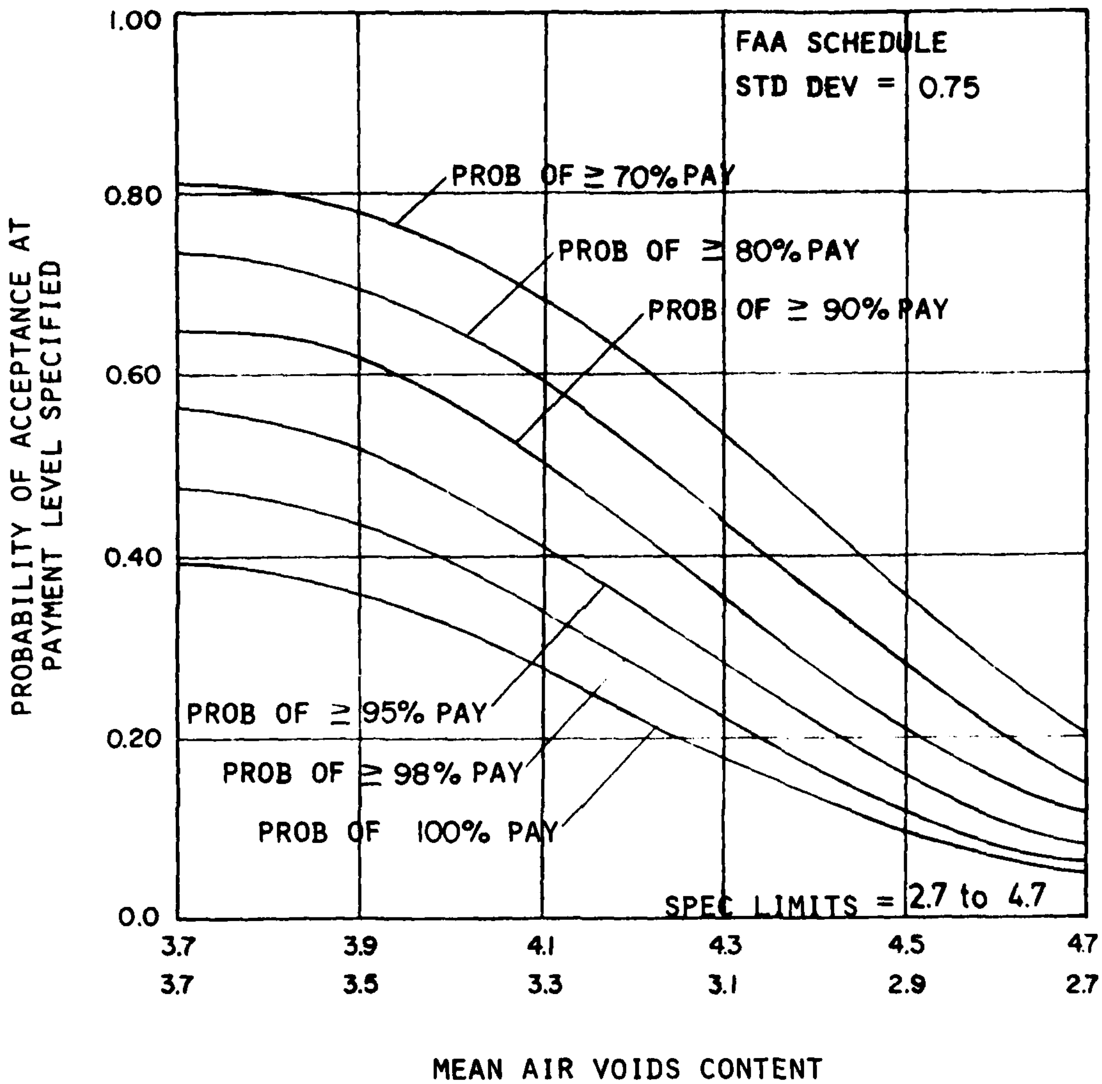

FIGURE 4.13 OPERATING CHARACTERISTICS FOR AIR VOIDS CONTENT USING FAA PRICE ADJUSTMENT SCHEDULE FOR A STANDARD DEVIATION OF 0.75

the specification range, are not very high. These curves were considered unacceptable, and it was decided that the acceptance plan required modification.

In all, five different price adjustment schedules were attempted. These schedules are presented in Table 4.8. The FAA schedule was used as a starting point, and modifications were made to this schedule in an attempt to provide expected payment curves which appeared reasonable. Expected payment curves were determined using the same assumptions as were made for the cases of stability and flow. The expected payment curves for Schedule I, III, and V are shown in Figure 4.14. None of these curves is ideal, but Schedule V seems to be the most reasonable; it was therefore selected for further use. The calculations for the curves in Figure 4.14 are shown in Table 4.9.

The OC curves price adjustment Schedule V are shown in Figures 4.15 through 4.17 for standard deviation values of 0.535, 0.75, and 0.95, respectively. The value of 0.75 corresponds to the pooled standard deviation values of 0.535, 0.75, and 0.95, respectively. The value of 0.75 corresponds to the pooled standard deviation of all the projects studied; 0.535 is the pooled standard deviation for the seven projects with the lowest standard deviations; and 0.95 indicates a project with below average control of air voids.

In order to consider the possibility that the pooled standard deviation value of 0.75 was too high, the expected payment curve was determined by using the FAA density price adjustment schedule (Table 4.6) for Marshall stability and flow and a standard deviation value of 0.535. This curve is presented in Figure 4.18, and the corresponding calculations are presented in Table 4.10. This curve appears to be even more appropriate than the one

TABLE 4.8 POSSIBLE PRICE ADJUSTMENT SCHEDULES FOR AIR VOIDS CONTENT

Schedule I

Estimated PWL	Percent Payment
90 and above	100
85 to 90	98
80 to 85	95
75 to 80	90
70 t0 75	80
65 to 70	70
Below 65	50

Schedule II

Estimated PWL	Percent Payment
90 and above	100
85 to 90	99
80 to 85	97.5
75 to 80	95
70 to 75	90
65 to 70	80
60 to 65	70
Below 60	50

Schedule III

Estimated PWL	Percent Payment
85 and above	100
80 to 85	98
75 to 80	95
70 to 75	90
65 to 70	80
60 to 65	70
Below 60	50

TABLE 4.8 (CONTINUED)

Schedule IV	
Estimated PWL	Percent Payment
85 and above	100
80 to 85	99
75 to 80	97.5
70 to 75	95
65 to 70	90
60 to 65	80
Below 60	50

Schedule V	
Estimated PWL	Percent Payment
80 and above	100
75 to 80	99
70 to 75	97.5
65 to 70	95
60 to 65	90
55 to 60	80
Below 55	50

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content of 3.9 are the same as for 3.5, etc.

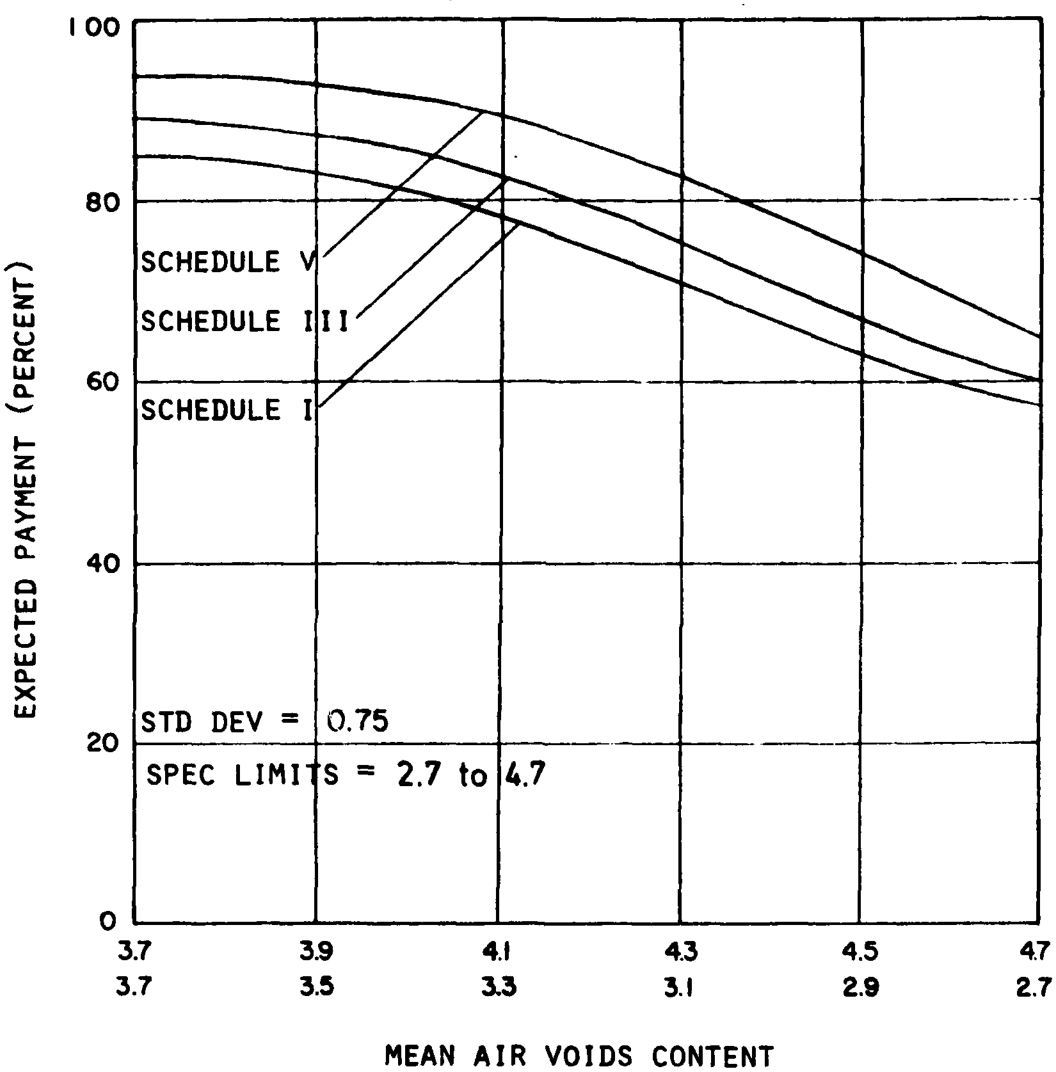

FIGURE 4.14 EXPECTED PAYMENT CURVES FOR THE PROPOSED PRICE ADJUSTMENT SCHEDULES FOR AIR VOIDS CONTENT FOR A STANDARD DEVIATION OF 0.75

TABLE 4.9 CALCULATIONS FOR THE EXPECTED PAYMENT CURVES FOR THE PROPOSED PRICE ADJUSTMENT SCHEDULES FOR AIR VOIDS CONTENT FOR A STANDARD DEVIATION OF 0.75 AND SPECIFICATION LIMITS 2.7 TO 4.7.

Proposed Price Adjustment Schedule I

Mean Value	Probability of Receiving Indicated Payment							Expected Payment
	100	98	95	90	80	70	50	
3.7	.399	.079	.088	.084	.088	.078	.184	85.3
3.9 (3.5)	.363	.079	.083	.087	.086	.086	.216	83.5
4.1 (3.3)	.283	.060	.071	.091	.092	.093	.310	78.5
4.3 (3.1)	.182	.048	.060	.069	.080	.100	.461	71.3
4.5 (2.9)	.096	.028	.037	.054	.068	.077	.638	63.4
4.7 (2.7)	.046	.013	.019	.029	.039	.059	.795	57.3

Proposed Price Adjustment Schedule III

Mean Value	Probability of Receiving Indicated Payment							Expected Payment
	100	98	95	90	80	70	50	
3.7	.478	.088	.084	.088	.078	.069	.115	89.1
3.9 (3.5)	.442	.083	.087	.086	.086	.077	.139	87.6
4.1 (3.3)	.343	.071	.091	.092	.093	.092	.218	83.0
4.3 (3.1)	.230	.060	.069	.080	.100	.104	.357	75.8
4.5 (2.9)	.126	.037	.054	.068	.077	.097	.541	67.5
4.7 (2.7)	.059	.019	.029	.039	.059	.072	.723	59.9

Proposed Price Adjustment Schedule V

Mean Value	Probability of Receiving Indicated Payment							Expected Payment
	100	99	97.5	95	90	80	50	
3.7	.566	.084	.088	.078	.069	.050	.065	94.4
3.9 (3.5)	.525	.087	.086	.086	.077	.059	.080	93.3
4.1 (3.3)	.414	.091	.092	.093	.092	.080	.138	89.8
4.3 (3.1)	.290	.069	.080	.100	.104	.102	.255	83.4
4.5 (2.9)	.163	.054	.068	.077	.097	.114	.427	74.8
4.7 (2.7)	.078	.029	.039	.059	.072	.096	.627	65.6

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content of 3.9 are the same as for 3.5, etc.

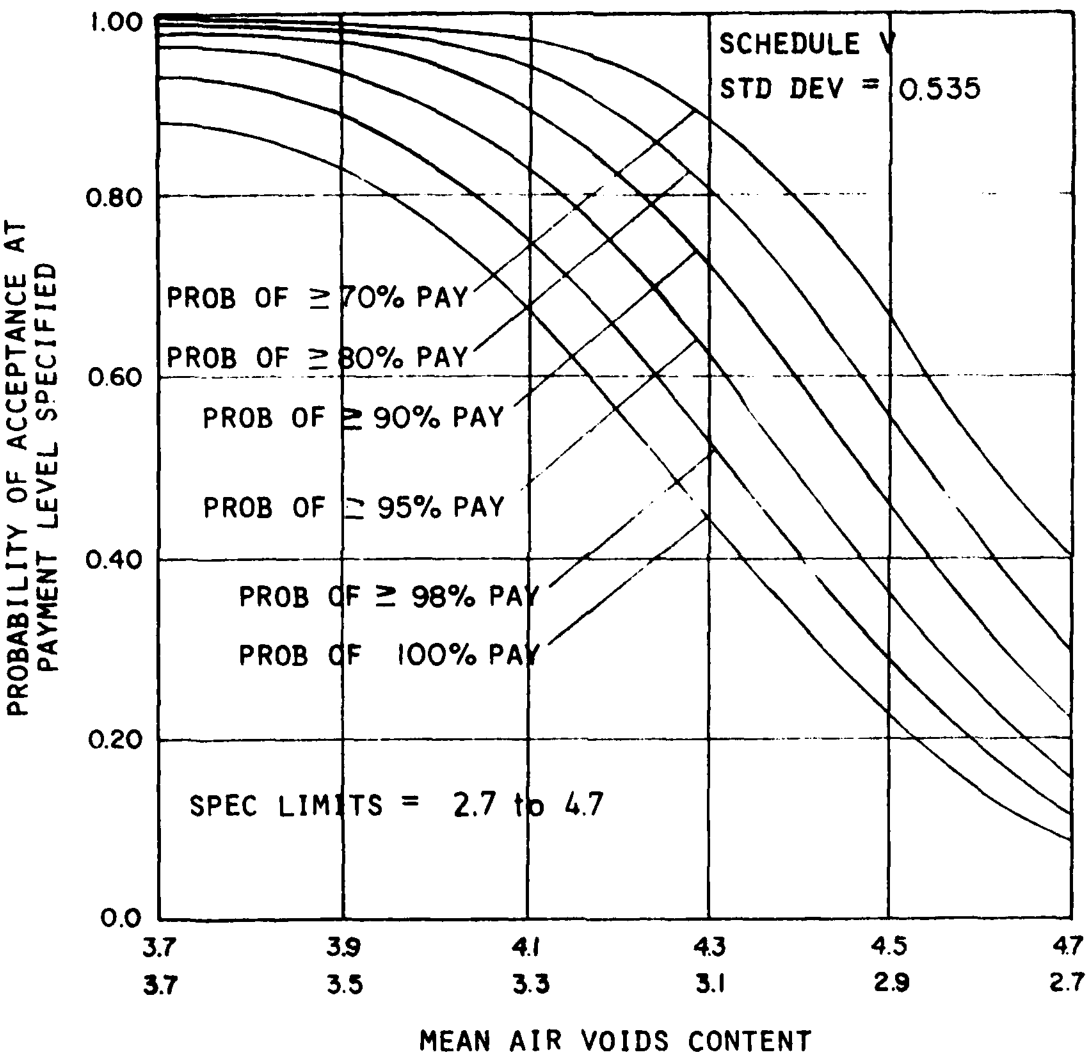

FIGURE 4.15 OPERATING CHARACTERISTICS FOR PROPOSED AIR VOIDS CONTENT PRICE ADJUSTMENT SCHEDULE V FOR A STANDARD DEVIATION OF 0.535

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content of 3.9 are the same as for 3.5, etc.

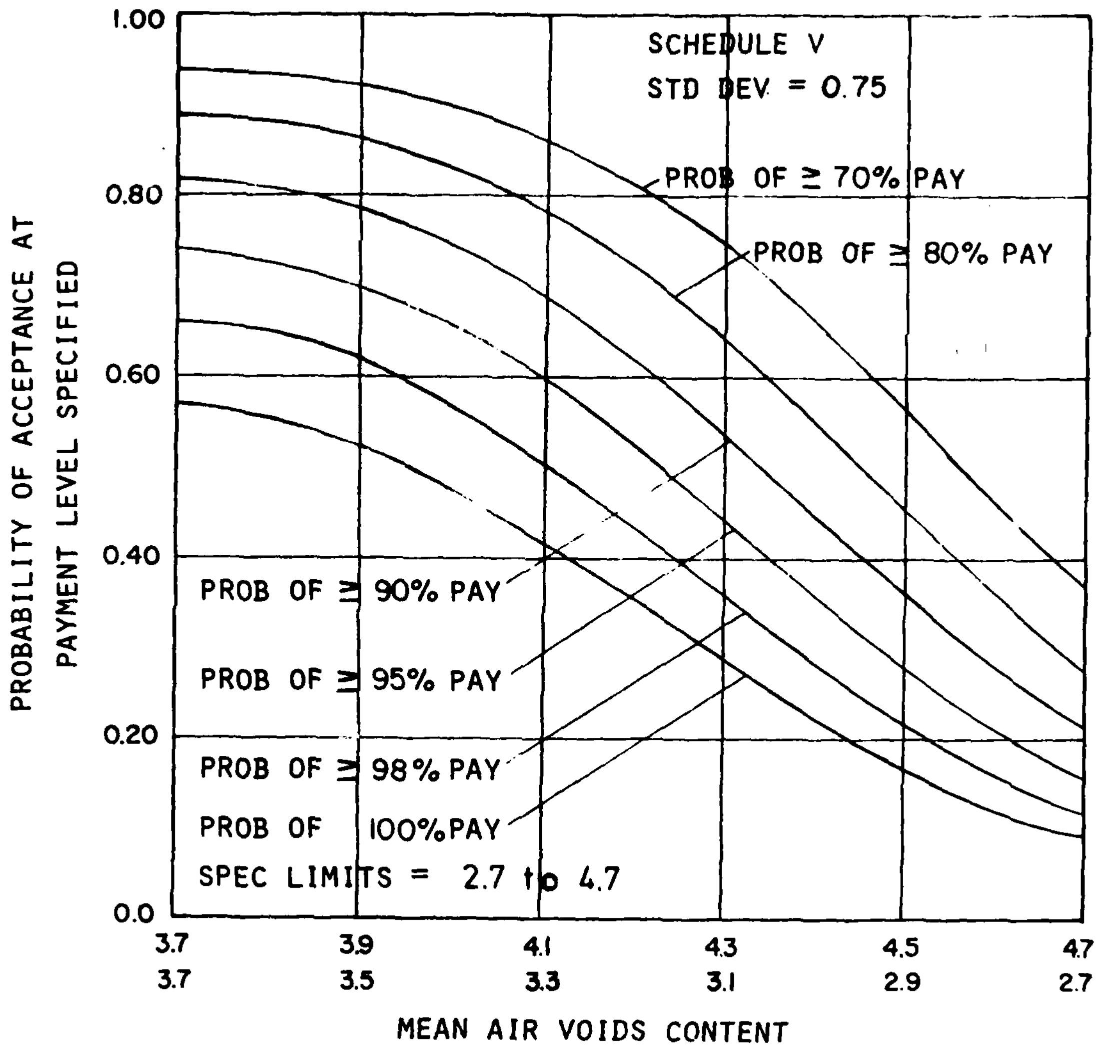

FIGURE 4.16 OPERATING CHARACTERISTICS FOR PROPOSED AIR VOIDS CONTENT PRICE ADJUSTMENT SCHEDULE V FOR A STANDARD DEVIATION OF 0.75

NOTE: Since this is a two-limit specification, the OC curves are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content or 3.9 are the same as for 3.5, etc.

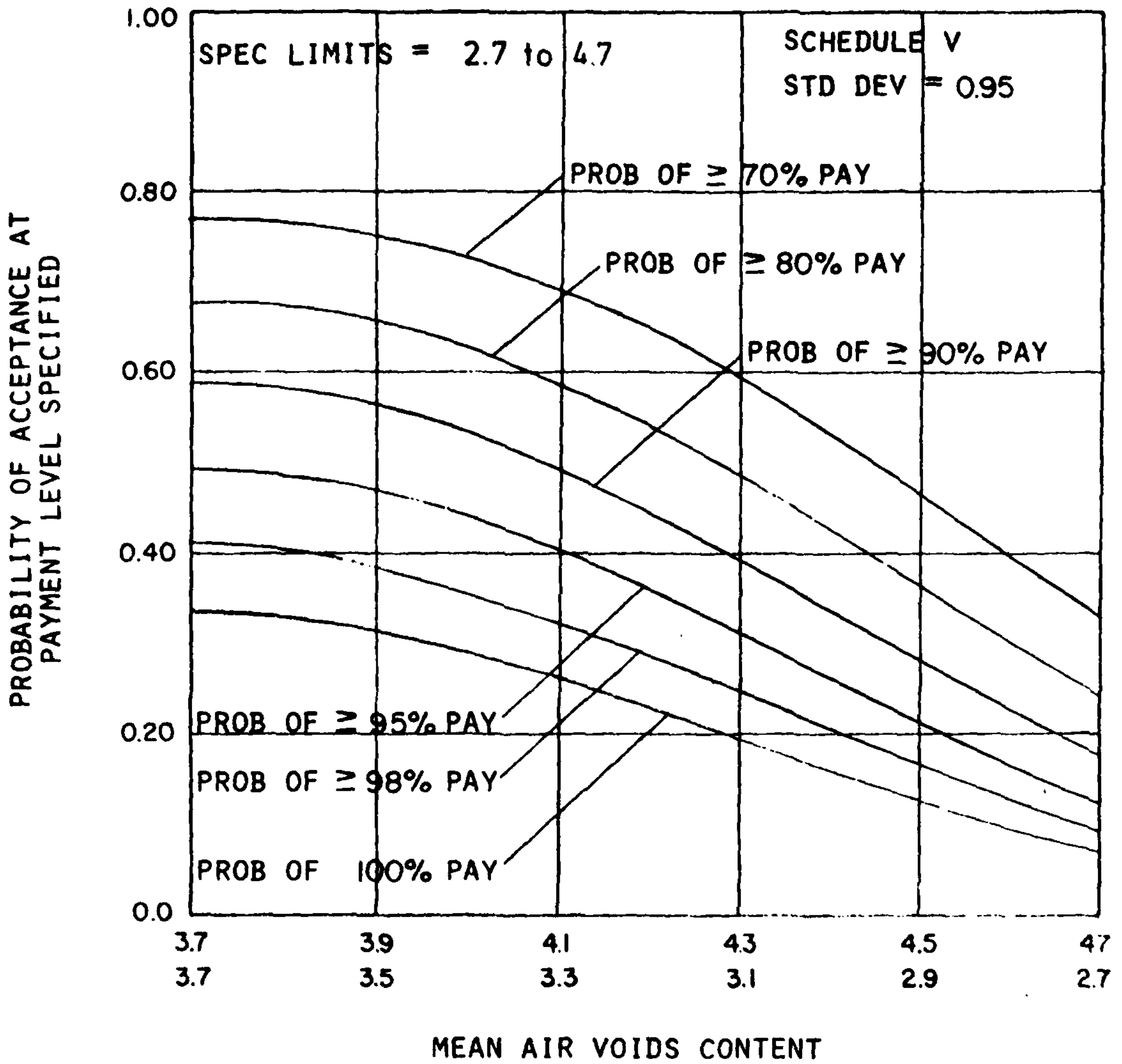

FIGURE 4.17 OPERATING CHARACTERISTICS FOR PROPOSED AIR VOIDS CONTENT PRICE ADJUSTMENT SCHEDULE V FOR A STANDARD DEVIATION OF 0.95

NOTE: Since this is a two-limit specification, the Expected Payment are symmetrical about the mean value in the center of the specification range (3.7 in this case). That is, the values obtained for a mean air voids content of 3.9 are the same as for 3.5, etc.

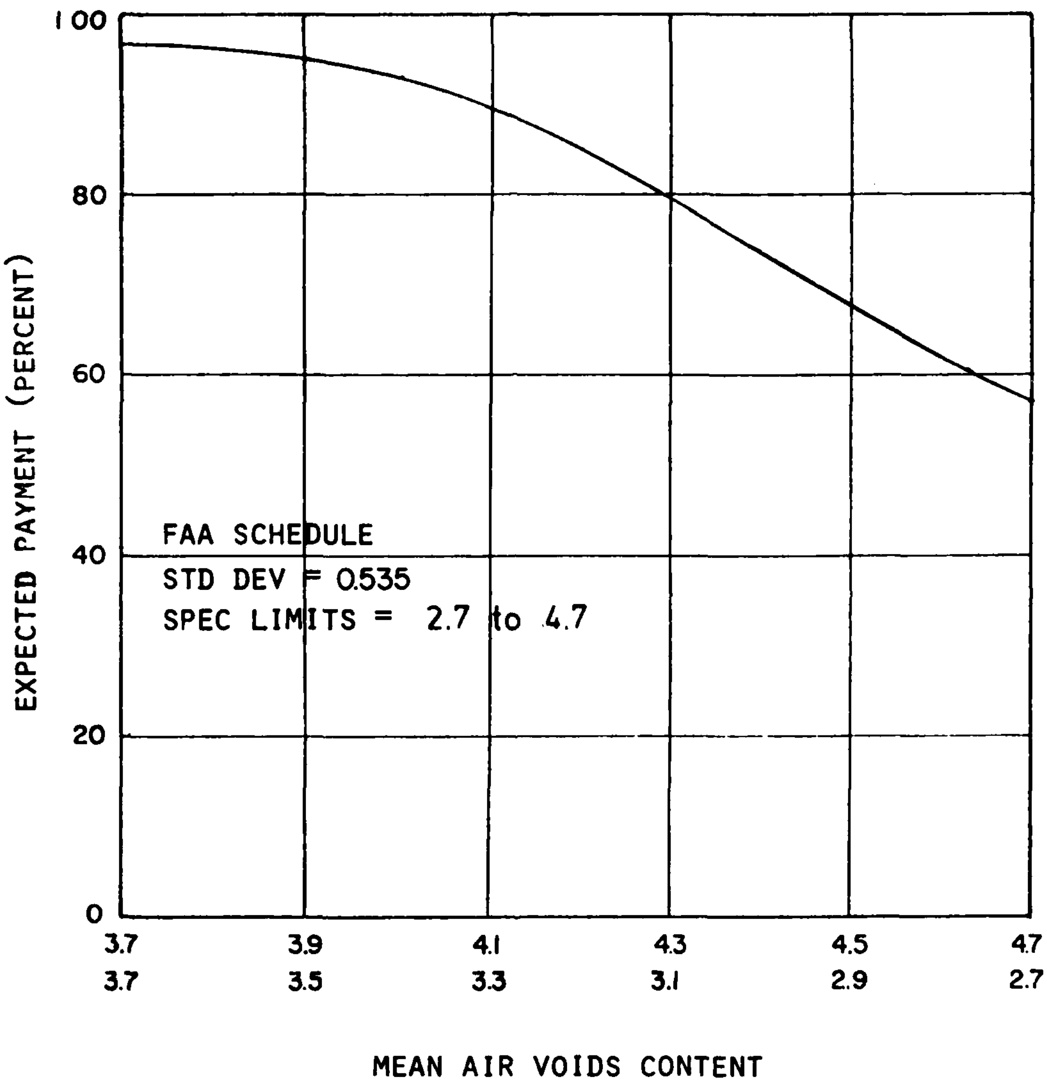

FIGURE 4.18 EXPECTED PAYMENT CURVE FOR AIR VOIDS CONTENT USING FAA PRICE ADJUSTMENT SCHEDULE FOR A STANDARD DEVIATION OF 0.535

TABLE 4.10 CALCULATIONS FOR THE EXPECTED PAYMENT CURVE FOR AIR VOIDS CONTENT USING THE FAA PRICE ADJUSTMENT SCHEDULE FOR A STANDARD DEVIATION OF 0.535 AND SPECIFICATION LIMITS OF 2.7 TO 4.7

Mean Value	Probability of Receiving Indicated Payment							Expected Payment
	100	98	95	90	80	70	50	
3.7	.745	.071	.065	.049	.033	.018	.019	96.9
3.9 (3.5)	.676	.080	.074	.058	.048	.031	.033	95.4
4.1 (3.3)	.506	.084	.088	.079	.076	.065	.102	90.0
4.3 (3.1)	.304	.065	.074	.092	.096	.098	.271	80.2
4.5 (2.9)	.136	.037	.054	.065	.078	.091	.539	67.8
4.7 (2.7)	.047	.014	.019	.030	.040	.064	.786	57.6

for price adjustment Schedule V, shown in Figure 4.14. If the FAA is willing to accept 0.535 as the standard deviation value for air voids, then the same price adjustment schedule proposed for Marshall stability and flow would seem reasonable. It is recommended that more data be collected before a decision to use 0.535 or 0.75 is made. If the problem of the effect of asphalt content variations on air voids calculations is resolved, and data are collected on future projects, then a decision can be made as to the appropriate standard deviation value and price adjustment schedule for air voids.

APPLYING PRICE ADJUSTMENTS

Until now, the price adjustment schedules for the Marshall properties have been considered individually. A question which must now be addressed is how the price adjustments will be assessed when more than one of the Marshall properties require price adjustments.

Multiple Price Adjustments

Since it is possible that the estimated PWL values for a particular lot of material may indicate price adjustments for more than one property, it is necessary to have a procedure to deal with this event. Two methods are most commonly used in dealing with multiple price adjustments. The first method uses the maximum price adjustment indicated as the price adjustment for the lot and ignores the other price adjustments. For example, if Marshall stability indicated a pay factor of 95 percent, Marshall flow a pay factor of 90 percent, and air voids a pay factor of 80 percent, then this method would allocate a pay factor of 80 percent to the lot of material.

The second method is to multiply the pay factors together to determine the pay factor for the lot of material. For the example above, this would

yield a pay factor for the lot of material of 0.95 x 0.90 x 0.80, or 68.4 percent. As can be seen from this example, the second method results in more severe price adjustments.

A third method that might be considered would be to determine the pay factor for the lot by summing the percentage reductions for each of the properties involved. For the example used before, this would provide a total price reduction for the lot of (1.0-0.95) + (1.0-0.90) + (1.0-0.80), or 35 percent. The pay factor for this lot would therefore be 65 percent. This method will yield the most severe price reductions.

The methods that attempt to apply more than one price adjustment to the lot, rather than using the largest one, assume that the properties are independent of one another. That is, if one of the properties measured is outside of the specification limits, then this does not necessarily mean that another property is outside of its specification limits. To see if this was the case for the properties used by FAA for acceptance, correlation tests were conducted on the Marshall test results for the projects in the study.

The results of these correlation tests are presented in Table 4.11. The correlation coefficients shown in this table can range from -1 for perfect negative correlation to +1 for perfect positive correlation. It was thought that if a high positive or negative correlation between any of the Marshall properties could be consistently identified, it might be possible to eliminate the need to measure all of these properties. However, there were no consistently high correlations between any of the test properties Some general trends did emerge. In most cases, stability and flow were positively correlated. And, in nearly every case, air voids correlated

TABLE 4.11 SUMMARY OF CORRELATION TESTS ON MARSHALL PROPERTIES FOR THE PROJECTS STUDIED

Project	Number of Tests	Correlation Coefficients: Stability and Flow	Stability and Air Voids	Flow and Air Voids
Adirondack - Type A	9	0.342	-0.773	-0.741
Adirondack - Type B	29	0.589	-0.609	-0.630
Charlottesville - ANJ	54	-0.241	-0.022	-0.029
Charlottesville - SLW	53	-0.548	0.335	-0.408
Chautauqua	27	0.324	-0.507	-0.354
Chemung - Chemung	24	0.441	0.014	-0.481
Chemung - Fisherville	56	0.458	-0.389	-0.381
DuBois	32	0.330	-0.271	-0.811
Dutchess	12	0.047	-0.431	-0.143
Linden	52	-0.062	-0.102	0.044
Westchester - Colprovia	99	0.243	-0.498	-0.287
Westchester - Peckham	85	0.132	-0.685	-0.587

negatively with stability and flow. It was considered, however, that the correlations were not strong enough to preclude measuring all three properties.

Recommendation for Applying Price Adjustments

The recommended method for applying multiple price adjustments is to multiply each of the pay factors together to determine the pay factor for the lot. It may be assumed that if all three properties are considered sufficiently important to measure, then the pavement should be less acceptable when two of these properties are outside acceptable limits than when only one of the properties is. If the price paid when the price adjustment calculations indicate pay factors of 100 percent for stability and flow and 80 percent for air voids is the same as the price paid when the calculations indicate pay factors of 80 percent for all three properties, this implies that the two cases are equally acceptable. If this is true, then all three properties should not be considered for price adjustments.

For the reason indicated above, it is recommended that some method of multiplying price adjustments together should be used. It should be noted, however, that the price adjustment schedules proposed for each of the Marshall properties may not necessarily work correctly for the case when multiple price adjustments are indicated. If this method is adopted, it may be necessary to increase the pay factors for a given estimated PWL value. It is difficult to determine how well a multiple property acceptance plan will perform until it is actually tried in the field. A simulation of the proposed price adjustment schedules was performed by applying them to the test results from three of the projects from the study. The results of this simulation are presented in Chapter 6. In addition, it is recommended that the FAA simulate the proposed price adjustments on selected projects in the upcoming construction season to evaluate their performance in the field.

After this field simulation, the performance of the price adjustment schedules could be analyzed and decisions about pay factors could be made by FAA prior to using the schedules for payment purposes on projects.

Even though it is intuitively appealing to multiply the price adjustment factors together, this approach is suggested with some reservations since no field experience has been obtained with this type of plan on FAA projects and the data obtained did not conclusively indicate that the Marshall properties were statistically independent. Further research is needed before a plan which multiplies payment factors is adopted by FAA. A field simulation of the use of such a plan on actual projects would allow FAA to compare the different methods for dealing with multiple price adjustments and, as a result, there would be more justification for the approach adopted.

5. ASPHALT CONTENT AND GRADATION

INTRODUCTION

In addition to density and Marshall properties, data were also collected on many of the projects for asphalt content and aggregate gradation. These properties are not currently used for acceptance purposes in the FAA Eastern Region P-401 specification, but it is required they be tested as a part of the contractor's quality control program. This chapter presents the findings of the analysis of the extraction test and theoretical hot bins results, which were supplied to the researchers by FAA. These results are compared with the quality control tolerance requirements stipulated in the Eastern Region P-401 specification. Finally, a discussion is presented of an attempt to correlate the results for asphalt content and gradation with those for the Marshall test results, and a more formal correlation program for these properties is recommended.

RESULTS OF THE ANALYSIS

Test results for asphalt content, extracted aggregate gradation, and theoretical hot bins gradation were provided to the researchers by FAA. The job mix formula (JMF) target values, mean production values, mean offsets from the JMF target values, and standard deviations for asphalt content for each of the projects that had results available are presented in Table 5.1. This table also presents the pooled values for mean and standard deviation for all of the projects combined.

The results of the analysis of the extracted aggregate gradations on a project-by-project basis are presented in Tables 5.2 through 5.10. The results of the theoretical mix gradation as calculated from hot bins

TABLE 5.1 RESULTS OF ASPHALT CONTENT TESTS FOR THE PROJECTS IN THE STUDY

Project	Number of Tests	JMF Value	Mean Value	Mean Offset from JMF Value*	Standard Deviation
Adirondack - Type A	10	5.4	5.67	+0.27	0.222
Adirondack - Type B	29	5.4	5.67	+0.27	0.178
Charlottesville - ANJ	45	4.9	4.88	-0.02	0.250
Charlottesville - SLW	40	6.4	6.41	+0.01	0.230
DuBois	18	6.3	6.28	-0.02	0.115
Dutchess	6	5.6	5.49	-0.11	0.211
Linden	26	6.1	6.04	-0.06	0.253
Richmond	38	6.0	5.50	-0.50	0.204
Westchester - Colprovia	40	6.3	6.01	-0.29	0.261
TOTAL	252				
POOLED VALUES		5.84	5.75	-0.09	0.235

*Specification tolerance limits are given in Table 5.17.

TABLE [illegible] EXTRACTED AGGREGATE GRADATION TESTS [illegible] THE [illegible]ONDACK - TYPE A PROJECT

Number of Tests = 10				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
1"	100	--	--	--
3/4"	92	87.6	-4.4	4.72
1/2"	78	76.6	-1.4	3.24
1/4"	65	62.5	-2.5	2.23
1/8"	48	47.4	-0.6	2.00
#20	38	36.6	-1.4	2.26
#40	28	27.9	-0.1	1.91
#80	14	13.6	-0.4	1.55
#200	5	5.3	+0.3	1.03

*Specification tolerance limits are given in Table 5.17.

TABLE 5.3 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE ADIRONDACK - TYPE B PROJECT

Number of Tests = 29				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
3/4"	100	--	--	--
1/2"	88	89.5	+1.5	2.71
1/4"	70	70.7	+0.7	2.45
1/8"	51	51.6	+0.6	1.65
#20	40	39.0	-1.0	1.83
#40	30	30.0	0.0	1.57
#80	14	15.3	+1.3	1.32
#200	6	6.3	+0.3	0.82

*Specification tolerance limits are given in Table 5.17.

TABLE 5.4 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE CHARLOTTESVILLE - ANJ PROJECT

Number of Tests = 45				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
3/4"	100	--	--	--
1/2"	89.0	87.4	-1.6	3.33
3/8"	79.9	79.0	-0.9	3.87
#4	61.6	63.4	+1.8	4.02
#8	51.5	52.0	+0.5	3.71
#16	37.4	36.3	-1.1	3.45
#30	24.4	24.0	-0.4	2.54
#50	14.9	15.4	+0.5	1.57
#100	9.5	10.7	+1.2	1.09
#200	5.3	7.6	+2.3	1.69

*Specification tolerance limits are given in Table 5.17.

TABLE 5.5 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE CHARLOTTESVILLE - SLW PROJECT

Number of Tests = 40				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
3/4"	100	--	--	--
1/2"	95.0	93.8	-1.2	2.03
3/8"	85.9	85.1	-0.8	3.19
#4	68.2	72.7	+4.5	3.42
#8	54.0	53.4	-0.6	3.86
#16	39.8	38.1	-1.7	3.17
#30	30.6	28.3	-2.3	2.48
#50	17.6	17.5	-0.1	3.12
#100	8.9	9.5	+0.6	1.21
#200	5.7	6.3	+0.6	1.12

*Specification tolerance limits are given in Table 5.17.

TABLE 5.6 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE DUBOIS PROJECT

Number of Tests = 18				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
1/2"	100	--	--	--
3/8"	93	97.4	+4.4	0.84
#4	73	75.3	+2.3	2.48
#8	53	52.3	-0.7	2.77
#16	36	36.0	0.0	2.14
#30	26	25.2	-0.8	1.62
#50	15	16.5	+1.5	0.98
#100	8	10.1	+2.1	0.60
#200	5	5.8	+0.8	0.45

*Specification tolerance limits are given in Table 5.17.

TABLE 5.7 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE DUTCHESS PROJECT

Number of Tests = 6				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
3/4"	100	--	--	--
1/2"	93.5	92.5	-1.0	1.12
1/4"	70.7	70.2	-0.5	1.87
1/8"	57.6	54.3	-3.3	1.45
#20	36.9	29.6	-7.3	1.28
#40	29.2	23.3	-5.9	1.49
#80	15.9	13.8	-2.1	1.36
#200	4.2	4.0	-0.2	0.98

*Specification tolerance limits are given in Table 5.17.

TABLE 5.8 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE LINDEN PROJECT

Number of Tests = 26				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
1/2"	100	--	--	--
3/8"	97.0	96.6	-0.4	1.58
#4	66.0	64.6	-1.4	2.72
#8	47.6	47.8	+0.2	1.69
#16	41.8	40.6	-1.2	1.61
#30	33.8	32.4	-1.4	1.95
#50	21.1	19.8	-1.3	1.77
#100	12.0	12.5	+0.5	1.55
#200	6.5	6.0	-0.5	0.68

*Specification tolerance limits are given in Table 5.17.

TABLE 5.9 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE RICHMOND PROJECT

Number of Tests = 38				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
3/4"	100	97.4	-2.6	1.83
1/2"	89	82.2	-6.8	3.16
3/8"	82	73.9	-8.1	3.10
#4	66	62.6	-3.4	2.71
#8	50	47.1	-2.9	2.23
#16	38	36.1	-1.9	1.93
#30	28	25.5	-2.5	1.57
#50	19	17.2	-1.8	1.28
#100	11	10.5	-0.5	1.27
#200	4.5	6.5	+2.0	1.22

*Specification tolerance limits are given in Table 5.17.

TABLE 5.10 RESULTS OF EXTRACTED AGGREGATE GRADATION TESTS FOR THE WESTCHESTER - COLPROVIA PROJECT

Number of Tests = 40				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value*	Standard Deviation
1"	100	--	--	--
3/4"	93	96.3	+3.3	2.08
1/2"	81	82.6	+1.6	3.52
3/8"	75	72.5	-2.5	3.74
#4	63	60.0	-3.0	3.15
#10	47	49.4	+2.4	3.05
#20	33	30.9	-2.1	2.97
#40	22	19.2	-2.8	2.47
#80	13	10.4	-2.6	1.81
#200	5	4.4	-0.6	0.66

*Specification tolerance limits are given in Table 5.17.

gradation are presented in Tables 5.11 through 5.15. A visual inspection of these tables shows little significant difference between them and the extracted gradations from Tables 5.2 through 5.10. Since only five projects have data available for theoretical hot bins gradation, and on one of these projects (Richmond) data are available only for a portion of the project, it was decided to concentrate only on the extracted aggregate gradation results.

The results of the extracted aggregate gradation tests for all of the projects studied are summarized in Table 5.16. This table includes all of the sieve sizes used in the study, the number of projects for which each sieve size was used, the total number of gradation tests in which each sieve size was included, and the pooled values for mean offset from the JMF value and standard deviation. Table 5.16 summaries the information presented in Tables 5.2 through 5.10. It can be seen that there is a tendency for the production mean values for the larger sieve sizes to fall below the JMF value, whereas for the small sieve sizes, #100 and #200, the reverse is true. Also, there is a general tendency for the standard deviation values to decrease as the sieve size, or percent of material passing, decreases.

COMPARISON OF RESULTS WITH QUALITY CONTROL REQUIREMENTS

As mentioned previously, extraction tests are not used for acceptance purposes, but they are required as part of the contractor's quality control (QC) program. The FAA Eastern Region specification requires that a minimum of two extraction tests and a minimum of two gradation tests, either on extracted aggregate or on hot bin samples, be performed daily. This specification also requires that the contractor control aggregate gradations and percent bitumen to within specified tolerances. These tolerances are

TABLE 5.11 RESULTS OF THEORETICAL HOT BINS AGGREGATE GRADATION TESTS FOR THE CHARLOTTESVILLE - ANJ PROJECT

Number of Tests = 27				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value	Standard Deviation
3/4"	100	--	--	--
1/2"	89.0	85.0	-4.0	3.50
3/8"	79.9	76.9	-3.0	3.74
#4	61.6	62.2	+0.6	3.99
#8	51.5	51.7	+0.2	4.02
#16	37.4	36.3	-1.1	3.31
#30	24.4	23.6	-0.8	2.30
#50	14.9	14.1	-0.8	1.76
#100	9.5	8.8	-0.7	1.90
#200	5.3	5.8	+0.5	1.85

TABLE 5.12 RESULTS OF THEORETICAL HOT BINS AGGREGATE GRADATION TESTS FOR THE CHARLOTTESVILLE - SLW PROJECT

Number of Tests = 50				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value	Standard Deviation
3/4"	100	--	--	--
1/2"	95.0	93.8	-1.2	1.01
3/8"	85.9	82.6	-3.3	3.02
#4	68.2	72.4	+4.2	5.43
#8	54.0	53.0	-1.0	5.08
#16	39.8	38.7	-1.1	4.23
#30	30.6	28.8	-1.8	3.35
#50	17.6	17.7	+0.1	2.02
#100	8.9	9.1	+0.2	1.43
#200	5.7	5.7	0.0	1.10

TABLE 5.13 RESULTS OF THEORETICAL HOT BINS AGGREGATE GRADATION TESTS FOR THE DUTCHESS PROJECT

Number of Tests = 12				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value	Standard Deviation
3/4"	100	--	--	--
1/2"	93.5	93.0	-0.5	0.42
1/4"	70.7	71.7	+1.0	1.37
1/8"	57.6	56.5	-1.1	1.07
#20	36.9	36.8	-0.1	2.82
#40	29.2	29.5	+0.3	2.72
#80	15.9	16.5	+0.6	1.76
#200	4.2	4.1	-0.1	0.97

TABLE 5.14 RESULTS OF THEORETICAL HOT BINS AGGREGATE GRADATION TESTS FOR THE RICHMOND PROJECT

Number of Tests = 12				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value	Standard Deviation
3/4"	100	99.4	-0.6	0.34
1/2"	89	89.6	+0.6	0.93
3/8"	82	81.9	-0.1	1.26
#4	66	69.4	+3.4	1.61
#8	50	52.8	+2.8	2.14
#16	38	39.0	+1.0	3.37
#30	28	26.4	-1.6	3.46
#50	19	17.7	-1.3	3.17
#100	11	11.0	0.0	3.15
#200	4.5	7.3	+2.8	2.91

TABLE 5.15 RESULTS OF THEORETICAL HOT BINS AGGREGATE GRADATION TESTS FOR THE WESTCHESTER - COLPROVIA PROJECT

Number of Tests = 95				
Sieve Size	JMF Value	Mean Value	Offset of Mean from JMF Value	Standard Deviation
1"	100	--	--	--
3/4"	93	95.9	+2.9	0.71
1/2"	81	82.1	+1.1	1.29
3/8"	75	72.1	-2.9	1.79
#4	63	60.2	-2.8	0.48
#10	47	50.6	+3.6	1.83
#20	33	33.2	+0.2	3.40
#40	22	20.6	-1.4	2.89
#80	13	10.2	-2.8	1.63
#200	5	4.0	-1.0	1.22

TABLE 5.16 SUMMARY OF THE RESULTS FOR EXTRACTED AGGREGATE GRADATIONS FOR THE PROJECTS IN THE STUDY

Sieve Size	Number of Projects	Number of Tests	Pooled Offset of Mean from JMF Value*	Pooled Standard Deviation
3/4"	3	88	-0.1	2.4
1/2"	7	208	-1.4	3.0
3/8"	6	207	-2.0	3.2
1/4"	3	45	-0.2	2.3
#4	7	207	+0.1	3.2
Combined #4 → 3/4"	--	755	-0.9	3.0
#8**	8	212	-0.6	2.9
#10	1	40	+2.4	3.0
#16	5	167	-1.3	2.7
#20	4	85	-2.0	2.5
#30	5	167	-1.5	2.2
#40	4	85	-1.7	2.1
#50	5	167	-0.3	2.0
#80	4	85	-1.0	1.6
Combined #80 → #8	--	1008	-1.0	2.4
#100	5	167	+0.7	1.2
#200	9	252	+0.8	1.1
Combined #200 → #100	--	419	+0.7	1.1

*Specification tolerance limits are given in Table 5.17.
**Includes those projects which indicated the use of 1/8" sieve size.

listed in Table 5.17, together with the pooled standard deviations from the projects studied. These tolerances and standard deviations can be compared in order to estimate how difficult it will be for these tolerances to be met.

Table 5.17 also includes values for the approximate percentage of a normal distribution centered at the target value and having a standard deviation, as shown in the table, that would fall within the tolerance limits. These values indicate that the tolerance limits may be too low in some cases. For material which passes sieves no. 8 through no. 80, nearly one test in ten can be expected to exceed the tolerance limits. It must also be remembered that the values shown in Table 5.17 are based on a process which is centered at the target value. The results in Table 5.16 indicate the actual production mean value is nearly always offset from the target value. This would lead to even more tests falling outside of the tolerance limits. It is recommended that these JMF tolerance limits be reevaluated in light of the results obtained from the projects' studied. The FAA may wish to consider an approach which establishes the tolerance limits at plus or minus two or three standard deviations from the target value. As can be seen from Table 5.17, for sieve sizes no. 8 through no. 80, current tolerance limits correspond to only plus or minus 1.67 standard deviations.

CORRELATION WITH MARSHALL PROPERTIES

Since, at the present time, both Marshall properties and extraction tests must be conducted on a daily basis, an attempt to correlate the test results for these two areas was made. It was hoped that if a strong correlation could be identified, then it might be possible to forego some of the tests. Since a contractor needs information concerning

TABLE 5.17 COMPARISON OF FAA JOB MIX FORMULA TOLERANCES WITH POOLED STANDARD DEVIATIONS OBTAINED FROM THE STUDY

Material	Tolerance Plus or Minus	Pooled Standard Deviation	Tolerance / Standard Deviation	Approximate Percentage Within Tolerance**
Aggregate passing No. 4 sieve or larger	7%	3.0	2.33	98.0
Aggregate passing Nos. 8, 10, 16, 20, 30, 40, 50 and 80 sieves	4%	2.4	1.67	90.5
Aggregate passing Nos. 100 and 200 sieves	2%	1.1	1.82	93.1
Bitumen	*0.4%**	*0.23*	1.74	91.8

*This tolerance will only be permitted if the JMF parameter curves indicate that the corresponding Marshall design parameters are not exceeded by their application.

**This refers to the percentage of a normal distribution which is centered at the target value and having a standard deviation as shown that would fall within the allowable tolerance limits.

the asphalt content and aggregate gradations for his process in any event, it was hoped that these tests could be used in place of the Marshall properties for acceptance purposes. This seemed reasonable since changes in Marshall properties are determined to a great extent by the asphalt content and aggregate gradations of the mix.

Problems Encountered

Because the available test results were not obtained from an experiment which was designed in advance, attempting to establish correlations was very difficult. Ideally, an extraction test should have been performed on one of the Marshall test specimens after the Marshall test was performed. In this way, the asphalt content and aggregate gradation for the Marshall specimen actually tested would be known. These results could then have been evaluated to determine if any of the Marshall properties were highly correlated with asphalt content or any particular sieve size.

A correlation between the Marshall test results and extraction test results was difficult to obtain because the tests were made on different samples and not on the same specimens. In an attempt to identify potential correlations, the Marshall test results and the extraction test results were each averaged on a daily basis for each project. The correlation coefficients for these daily Marshall and extraction values were then determined for each of the projects (Tables 5.18 through 5.20). As can be seen from the tables, no consistently high correlations were identified. These results should be considered highly unreliable, however, in light of the manner in which the data were collected and the make-shift method used in developing the correlation coefficients. It is quite possible that a properly designed correlation program could identify relationships between the results of Marshall tests and extraction tests.

TABLE 5.18 CORRELATION COEFFICIENTS FOR MARSHALL STABILITY VERSUS EXTRACTION TEST RESULTS

Project	Asphalt Content	Sieve Size															
		3/4"	1/2"	3/8"	1/4"	#4	1/8"	#8	#10	#16	#20	#30	#40	#50	#80	#100	#200
Adirondack - Type A	-.90	-.26	-.91		-.43		-.37				-.10		+.02		+.39		+.52
Adirondack - Type B	-.09		+.09		-.24		-.38				-.24		-.02		+.37		+.77
Charlottesville - ANJ	+.30		-.41	-.37		-.39		-.37		-.27		-.27		-.36		-.42	+.14
Charlottesville - SLW	-.56		-.04	-.29		-.36		-.17		-.07		+.07		-.06		-.26	-.19
DuBois	-.34			+.05		+.49		+.51		+.48		+.47		+.64		+.49	+.13
Dutchess	-.14		+.92		+1.0		+1.0				-.72		-.82		-.95		-.57
Linden	+.01			+.21		+.18		-.28		-.19		-.23		-.50		+.39	+.10
Westchester - Colprovia	-.25	-.14	-.38	-.34		-.34			-.31		-.24		-.21		-.37		-.59

TABLE 5.19 CORRELATION COEFFICIENTS FOR MARSHALL FLOW VERSUS EXTRACTION TEST RESULTS

Project	Asphalt Content	Sieve Size															
		3/4"	1/2"	3/8"	1/4"	#4	1/8"	#8	#10	#16	#20	#30	#40	#50	#80	#100	#200
Adirondack - Type A	-.36	+.47	-.39		+.30		+.36				+.61		+.69		+.91		+.96
Adirondack - Type B	-.06		+.51		-.06		-.41				-.55		-.39		+.06		+.62
Charlottesville - ANJ	-.24		-.18	-.27		-.22		-.40		-.31		-.23		-.11		+.06	-.14
Charlottesville - SLW	-.08		-.32	-.32		-.07		-.11		-.23		-.35		+.01		+.03	+.23
DuBois	+.14			+.44		-.12		-.49		-.51		-.44		-.16		+.53	+.82
Dutchess	-.93		+.17		-.16		-.24				+.84		+.75		-.08		-.66
Linden	-.10			-.54		+.20		+.66		+.37		+.27		+.43		-.69	+.01
Westchester - Colprovia	-.14	-.19	-.38	-.29		-.35			-.45		-.26		-.15		-.05		+.29

TABLE 5.20 CORRELATION COEFFICIENTS FOR AIR VOIDS CONTENT VERSUS EXTRACTION TEST RESULTS

Project	Asphalt Content	Sieve Size															
		3/4"	1/2"	3/8"	1/4"	#4	1/8"	#8	#10	#16	#20	#30	#40	#50	#80	#100	#200
Adirondack - Type A	+.84	+.15	+.86		+.33		+.27				-.01		-.13		-.48		[illegible]
Adirondack - Type B	+.05		-.40		+.09		+.43				+.61		+.40		-.09		[illegible]
Charlottesville - ANJ	-.46		+.47	+.38		+.45		+.47		+.47		+.47		+.48		+.45	[illegible]
Charlottesville - SLW	-.36		+.12	-.06		-.46		-.07		+.17		+.29		+.16		-.06	-.20
DuBois	-.26			-.46		+.06		+.37		+.37		+.31		-.00		-.63	[illegible]
Dutchess	-.12		-.78		-.95		-.97				+.88		+.94		+.84		[illegible]
Linden	+.29			+.33		+.01		-.11		-.40		-.42		-.36		-.15	[illegible]
Westchester - Colprovia	+.17	+.15	+.41	+.26		+.40			+.41		+.42		+.46		+.33		[illegible]

Price Adjustments

Because unreliable results were obtained from the attempted correlation study, development of price adjustments for asphalt content and aggregate gradations was not attempted. If price adjustments are applied for Marshall properties, then it would be unfair to apply price adjustments for asphalt contents and gradations since changes in these latter properties will probably be reflected in the Marshall properties. It is recommended that as long as the Marshall properties are used for acceptance purposes, asphalt content and gradations should remain as quality control tests and should not be considered for price adjustments.

Recommended Correlation Program

It is recommended that a program be considered which would attempt to correlate the results of Marshall tests with extraction tests. Such a program could also include the effects of these properties on the mat density achieved. Such a program might involve taking replicate samples from the same truck and conducting Marshall tests on the samples. The Marshall specimens (probably one specimen from each sample) could then be used for extraction tests. In this way, it would be possible to obtain some estimate of the sampling variability as well as to identify possible correlations between the Marshall properties and the extraction test results.

This program could be extended by marking the trucks from which the Marshall specimens were drawn, and subsequently marking the location in the pavement at which this material was placed. If the same rolling pattern were used in all cases, then it might be possible to estimate the effect of varying asphalt contents and aggregate gradation on the field density obtained.

A correlation between the results obtained from nuclear density measurements and cores could also be investigated. When the field density is determined in accordance with the above correlation program, nuclear density measurements could first be taken at each location, and then cores could be drilled at the same spot. This would allow a determination of the relationship between the density obtained by nuclear devices and by cores. It might also resolve the question whether varying asphalt contents and aggregate gradations affect these density measurements in the same fashion.

6. SIMULATION OF ACCEPTANCE PLAN

INTRODUCTION

To evaluate the appropriateness of the proposed acceptance plans, they were applied to the test results from three of the projects. This chapter first presents a summary of each of the proposed acceptance plans and a description of their application in the field. Then the simulation of the acceptance plans is presented and discussed.

DENSITY ACCEPTANCE PLAN

The proposed density acceptance plan is very similar to the one which was used during the 1978 construction season. The primary difference lies in the manner in which price adjustments are determined. The FAA price adjustment schedule (Table 6.1) was taken from the FAA Eastern Region P-401 specification. The price adjustment schedule for the proposed acceptance plan is presented in Table 6.2. The proposed plan has a continuous, rather than discrete, price adjustment schedule, in which the payment level is determined by entering the estimated PWL into the appropriate formula. The major points concerning the application of the proposed acceptance plan are the following:

1. Acceptance is to be on a lot-by-lot basis, with a lot defined as one day's production. The definition of lots that appears in EA AS 5370.2A, Appendix 1, section 401-4.14 (Eastern Region P-401 Specification) should still be appropriate for the proposed new acceptance plan.
2. Density acceptance is to be based on the estimated percentage of the material which is above the specification lower tolerance limit (PWL). The specification lower tolerance is set at 96.7 percent.

TABLE 6.1 PRICE ADJUSTMENT SCHEDULE FROM FAA DENSITY ACCEPTANCE PLAN

Percent Above Lower Tolerance Limit	Percent of Contract Price to be Paid
90-100	100
85-89	98
80-84	95
75-79	90
70-74	80
65-69	70
Less than 65	*

*The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu thereof, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall not be removed and will be paid for at 50 percent of the contract unit price.

TABLE 6.2 PRICE ADJUSTMENT SCHEDULE FOR THE PROPOSED DENSITY ACCEPTANCE PLAN

Estimated Percentage of Material Above the Specification Limit (PWL)	Percent of Contract Price to be Paid
90-100	100
80-90	0.5 PWL + 55.0
65-80	2.0 PWL - 65.0
Below 65	*

*The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu thereof, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall not be removed and will be paid for at 50 percent of the contract price.

3. The method for estimating PWL is similar to the method described in section 401-4.17(e) of the Eastern Region specification, except that the standard deviation method rather than the range method is to be used to calculate the Quality Index, QL. The Quality Index is determined from the following formula:

$$Q_L = \frac{\bar{X}-L}{S}$$

where: $\bar{X}$ = mean of the measurements on the lot

L = specification lower tolerance limit (96.7%)

S = standard deviation of the measurements on the lot.

Once the value of Q_L has been determined, the estimated PWL value can then be found from Table 3.5.

4. The price adjustment for the lot, if needed, is determined by substituting the estimated PWL value into the appropriate equation in Table 6.2. It is recommended that some guidelines be developed to guarantee that the price adjustments are determined in the same way on all projects. These guidelines might consist of determining the estimated PWL value to the nearest 0.1 by linear interpolation in Table 3.5 and then using this value in the equations in Table 6.2 to determine the price adjustment to the nearest 0.1 percent. The content of the guidelines is not as important as the fact that some guidelines are used. Guidelines will ensure that the price adjustments are being applied uniformly on all projects.

5. The option of using nuclear density devices for determining density for acceptance purposes can be maintained in the proposed acceptance plan. However, the specification lower tolerance limit should be 96.7 percent rather than the value of 97.0 percent which was used in the Eastern Region P-401 specification.

[illegible]ES ACCEPTANCE PL[illegible]

[illegible] acceptance plans [illegible] properties of stabil[illegible] [illegible] are based as [illegible] as [illegible]ible on features already [illegible] the Eastern Region P-401 spec[illegible] for the 1978 construction [illegible] The price adjustment schedule for stab[illegible] and flow is the same one used for density in the Eastern Region specification. This schedule was presented in Table 4.6. The FAA price adjustment schedule for air voids had to be modified as a consequence of the high value for standard deviation obtained from the projects studied. The price adjustment schedule for air voids was presented as Schedule V in Table 4.8. The major points concerning the application of the proposed acceptance plans are the following:

1. Acceptance is to be on a lot-by-lot basis, with a lot defined as one day's production. Since Marshall samples, unlike density samples, are taken during production rather than after production is completed, problems concerning lot size and the number of samples required per lot can arise when production is terminated early. The requirements for the number of samples per lot (401-14[a]) and for partial lots (401-17[c]) for the case of Marshall properties are stated in the Eastern Region P-401 specification. In the specification, acceptance is based on four samples per lot, with the following provisions for handling partial lots when production is terminated before four samples have been taken (22):

> For stability, flow and air voids determinations, if less than three tests have been made on the partially completed lot, the material and the number of tests from the partially completed lot will be combined with the most recently completed lot. If three tests have been made on the partially completed lot, the amount of material will be defined as a lot and the three tests which have been made will be used as the number of tests for that lot.

These guidelines seem reasonable. Their use allows for a range of possible sample sizes of from three to six. All of these sample sizes are included in Table 3.5 for estimating PWL.

2. Acceptance for Marshall properties is to be based on the estimated percentage of the material which is within the specification tolerance limits (PWL) listed in the Eastern Region P-401 specification. For stability, a lower specification tolerance limit of 1800 pounds is required. For flow and air voids, both lower and upper specification tolerances are indicated: 8 and 16 for flow, and 2.7 percent and 4.7 percent for air voids.

3. The method for estimating PWL for the case of stability is identical to the case of density, since only a lower tolerance limit is required. The procedure is somewhat different for the case of flow or air voids since both upper and lower limits are required. In the latter instance, two Quality Indexes, Q_U and Q_L, are determined from the following:

$$Q_U = \frac{U-\overline{X}}{S} \quad \text{and} \quad Q_L = \frac{\overline{X}-L}{S}$$

where: $\overline{X}$ = mean of the measurements on the lot

U = specification upper tolerance limit

L = specification lower tolerance limit

S = standard deviation of the measurements on the lot.

Once the calculations have been completed, the value of Q_U can be used together with Table 3.5 to determine the estimated percentage of the material below the upper limit (PWL_U). Similarly, the value of Q_L can be used to determine the estimated percentage

of the material above the lower limit (PWL_L). The PWL estimate for the lot can then be determined from the following relationship:

$$PWL = PWL_U + PWL_L - 100.$$

4. The price adjustment for each of the properties, if needed, is determined from Table 4.6 for the case of stability and flow, and from Table 4.8 for the case of air voids. The price adjustment for Marshall properties for the lot of material is then the product of the three individual pay factors (in decimal form) for stability, flow, and air voids.

TOTAL PAY FACTOR

On some lots of material, price adjustments may be indicated for both density and the Marshall properties. Some procedure must, therefore, be developed for dealing with multiple price adjustments. The same methods may be used in this case as were used to determine the total price adjustment for the Marshall properties. The larger price reduction, either that for density or the Marshall properties, can be taken as the price adjustment for the lot, or the product of the individual price adjustments for density and the Marshall properties can be used. If it is assumed that the pavement is less acceptable when both density and the Marshall properties are outside tolerance limits than when only one of these is outside the limits, then the latter method seems preferable and is the one that was used when the acceptance plans were simulated.

However, even though this approach is the most intuitively appealing, potential problems with this approach could result because the Marshall properties are related to the batch plant and density is related to the field

construction. If the materials supplier and field contractor are not the same party, assessing multiplicative price adjustments could be difficult and could have potential legal implications. This topic, which has not been addressed to a great extent in the literature, requires additional research. In the simulation of the acceptance plans on the projects, this approach was used to illustrate what can happen when the price adjustment factors are multiplied together. The multiplicative approach used here should be employed in a field simulation by the FAA during the upcoming construction season in order to evaluate its performance. The multiplicative approach could be evaluated by comparing it with other methods, such as the use of the largest price reduction (Marshall properties or density) or the application of price adjustments for Marshall properties and density as separate bid items.

SIMULATION OF THE ACCEPTANCE PLANS

The application of the proposed acceptance plans was simulated on the test results of three projects from the study. The projects were chosen for the simulation because the information available for these projects was most appropriate. Many projects were not performed under the Eastern Region specifications, and several of these required only two Marshall tests per day. Since the proposed acceptance plans call for four samples per day, it was desirable for the simulation to find projects on which four Marshall tests had been conducted per day. It was also considered preferable to simulate the acceptance plans on projects which had daily production tonnage available.

The three projects which were identified as being most appropriate for the simulation were Adirondack - Type B, Charlottesville - ANJ, and Linden.

The various conditions on these projects are typical of the projects that may be encountered in the field. An examination of the results of the density analysis shown in Table 3.1 indicates that the Linden project exhibited the best density control (mean of 98.53, standard deviation of 0.45) and the Charlottesville - ANJ project exhibited the poorest density control (mean of 97.58, standard deviation of 2.14) of all the projects studied. The Adirondack project exhibited a level of density control (mean of 98.83, standard deviation of 1.14) which was the closest of any project to the pooled standard deviation of 1.19.

Concerning the Marshall properties results in Tables 4.1 through 4.3, the Linden project exhibited excellent control for stability (offset of -53.1, standard deviation of 127.45), whereas the Adirondack - Type B project (offset -43.4, standard deviation of 256.46) and the Charlottesville - ANJ project (offset +402.6, standard deviation of 271.32) exhibited a level of control that was very near the pooled standard deviation of 279. All three of the projects had standard deviations for flow values which were below the pooled value for all the projects. The mean flow value (11.90) for the Linden project was nearly in the center of the specification range (8-16), whereas the value for Adirondack - Type B (10.02) was closer to the lower limit. The mean flow value for Charlottesville - ANJ (15.91) was nearly equal to the upper tolerance limit, thus indicating that a great deal of the material will be found to be outside the specification limits.

All three of the projects had standard deviation values for air voids (0.623, 0.577, 0.684) that were lower than the pooled value (0.75). The mean values for Adirondack - Type B (3.58) and for Linden (3.86) were near

the center of the allowable range (2.7-4.7). One factor to be considered regarding the Charlottesville - ANJ project is that the specification range for air voids was different than for the other projects. The lower and upper limits for the air voids on this project were 2.0 and 4.0, respectively. These values were used for L and U when calculating the Q_L and Q_U values used for estimating PWL.

Results of Simulation

The results of the simulation of the acceptance plans for density are shown in Tables 6.3 through 6.5. These tables show the calculations necessary for arriving at the estimated PWL value by means of the recommended standard deviation method. Also shown are the value of percent payment which would be made for each lot under the proposed acceptance plan. These percent payments can be compared with the payments that would have been made under the FAA price adjustment schedule, using the range method for estimating PWL. In most cases there is close agreement between the payment factors for the two methods. There are, however, some major differences on the Charlottesville - ANJ project. For example, on October 31, 1978, the proposed plan indicates a payment of 77.4 percent, while the FAA plan yields a payment of only 70 percent; on November 2, 1978, the proposed plan indicates a payment of 95.5 percent as compared with 90 percent for the FAA plan. These differences arise from the different values obtained for the estimated PWL by using the standard deviation method versus the range method.

The results of the simulation for the Marshall properties acceptance plan are presented in Tables 6.6 through 6.8. As expected, there were very few problems in meeting the stability and flow requirements, with the major

TABLE 6.3 CALCULATIONS OF PRICE ADJUSTMENTS FOR DENSITY FOR THE SIMULATION ON THE ADIRONDACK - TYPE B PROJECT (SPECIFICATION LOWER LIMIT = 96.7)

Date	Mean	Standard Deviation	Sample Size	Quality Index Q	Estimated PWL*	Percent Payment (Proposed Plan)	Percent Payment (FAA Plan)
9/29	98.8	.640	4	3.281	100	100	100
9/30	99.3	.436	4	5.963	100	100	100
10/2	98.5	1.600	4	1.125	87.5	98.8	100
10/3	99.9	.755	4	4.238	100	100	100
10/4	99.1	.645	4	3.721	100	100	100
10/5	99.8	.789	4	3.929	100	100	100
10/11	98.1	1.000	4	1.400	96+	100	100
10/12	99.1	.737	4	3.256	100	100	100
10/16	97.8	1.318	4	0.835	77.8	90.6	90
10/17	99.5	.532	4	5.263	100	100	100

*PWL values are determined to one decimal place only when this value is necessary for determining percent payment under the proposed plan.

TABLE 6.4 CALCULATIONS OF PRICE ADJUSTMENTS FOR DENSITY FOR THE SIMULATION ON THE CHARLOTTESVILLE - ANJ PROJECT (SPECIFICATION LOWER LIMITS = 96.7)

Date	Mean	Standard Deviation	Sample Size	Quality Index Q	Estimated PWL*	Percent Payment (Proposed Plan)	Percent Payment (FAA Plan)
10/17	99.4	1.282	4	2.106	100	100	100
10/18	99.7	.742	4	4.043	100	100	100
10/19	100.1	.294	4	11.565	100	100	100
10/20	98.2	1.034	4	1.384	96+	100	100
10/21	99.3	1.400	3	1.857	100	100	100
10/23	98.2	1.580	4	0.949	81.6	95.8	95
10/24	98.1	1.127	4	1.242	91+	100	100
10/25	99.2	1.103	4	2.267	100	100	100
10/26	98.1	.954	3	1.468	100	100	100
10/27	97.4	2.359	6	0.297	60+	50**	50**
10/28	95.3	2.791	4	-0.502	33+	50**	50**
10/31	97.2	.787	4	0.635	71.2	77.4	70
11/1	96.4	1.424	4	-0.211	40+	50**	50**
11/2	98.0	1.398	4	0.930	81.0	95.5	90
11/3	96.4	1.034	4	-0.290	40+	50**	50**
11/4	95.6	2.767	4	-0.398	37-	50**	50**
11/6	94.1	2.835	4	-0.977	20+	50**	50**

*PWL values are determined to one decimal place only when the value is necessary for determining percent payment under the proposed plan.
**Remove and replace or accept a 50 percent payment.

TABLE 6.5 CALCULATIONS OF PRICE ADJUSTMENTS FOR DENSITY FOR THE SIMULATION ON THE LINDEN PROJECT

Date	Mean	Standard Deviation	Sample Size	Quality Index Q	Estimated PWL	Percent Payment (Proposed Plan)	Percent Payment (FAA Plan)
11/10	98.87	.579	7	3.75	100	100	100
11/13	98.64	.685	7	2.83	100	100	100
11/14	98.54	.355	7	5.18	100	100	100
11/15	98.37	.382	7	4.37	100	100	100
11/16	98.46	.374	7	4.71	100	100	100
11/17	98.17	.138	7	10.65	100	100	100
11/20	98.06	.162	7	8.40	100	100	100
11/21	98.66	.257	7	7.63	100	100	100
11/22	98.59	.241	7	7.84	100	100	100
11/24	98.90	.216	7	10.19	100	100	100
11/29	98.84	.151	7	14.17	100	100	100
11/30	98.54	.199	7	9.25	100	100	100
12/1	97.90	.370	7	3.24	100	100	100

TABLE 6.6 CALCULATIONS OF PRICE ADJUSTMENTS FOR MARSHALL PROPERTIES FOR THE SIMULATION ON THE ADIRONDACK - TYPE B PROJECT

Date	Mean Value	Standard Deviation	Sample Size	Quality Index Q_U	Quality Index Q_L	Estimated PWL	Percent Payment*
Marshall Stability (Spec Limit = 1800)							
9/29 and 9/30	2303.8	220.7	4	2.283		100	100
10/2	2217.0	276.3	3	1.509		100	100
10/3	2286.0	228.1	4	2.131		100	100
10/4 and 10/5	2342.2	361.6	5	1.499		96+	100
10/11	2637.0	165.0	4	5.073		100	100
10/12	2252.0	172.3	4	2.623		100	100
10/16 and 10/17	2344.8	298.0	4	1.828		100	100
Marshall Flow (Spec Limits = 8 to 16)							
9/29 and 9/30	10.2	1.33	4	1.654	4.361	100	100
10/2	9.4	2.08	3	0.673	3.173	69+	70
10/3	9.2	0.81	4	1.482	8.395	99+	100
10/4 and 10/5	10.2	1.73	5	1.272	3.535	91+	100
10/11	11.2	1.84	4	1.739	2.609	100	100
10/12	10.1	1.14	4	1.842	5.175	100	100
10/16 and 10/17	10.0	1.41	4	1.418	4.255	97+	100
Air Voids (Spec Limits = 2.7 to 4.7)							
9/29 and 9/30	3.4	0.560	4	1.250	2.321	91+	100
10/2	4.3	0.404	3	3.960	0.990	82+	100
10/3	3.8	0.457	4	2.407	1.969	100	100
10/4 and 10/5	3.5	0.581	5	1.377	2.065	93+	100
10/11	2.9	0.356	4	0.562	5.056	68+	95
10/12	3.7	0.129	4	7.752	7.752	100	100
10/16 and 10/17	3.6	0.936	4	0.962	1.175	71+	97.5

*Payment levels indicated are for the individual properties, i.e., stability, flow, or air voids.

TABLE 6.7 CALCULATIONS OF PRICE ADJUSTMENTS FOR MARSHALL PROPERTIES FOR THE SIMULATION ON THE CHARLOTTESVILLE - ANJ PROJECT

Date	Mean Value	Standard Deviation	Sample Size	Quality Index Q_L	Quality Index Q_U	Estimated PWL	Percent Payment*
Marshall Stability (Spec Limit = 1800)							
10/16 and 10/17	2566.2	293.9	6	2.607		100	100
10/18	2854.0	514.8	4	2.047		100	100
10/19	2606.3	457.6	3	1.762		100	100
10/20	2575.3	175.7	4	4.413		100	100
10/21	2819.7	99.0	3	10.300		100	100
10/23	2839.7	345.5	3	3.009		100	100
10/24	2851.0	106.2	4	9.896		100	100
10/25	2348.3	32.0	3	17.134		100	100
10/26	2592.8	160.9	4	4.927		100	100
10/27	2963.7	130.1	3	8.945		100	100
10/28 and 10/30	2940.0	36.1	3	31.579		100	100
10/31 and 11/1	2763.4	147.9	5	6.514		100	100
11/2	2889.0	113.6	3	9.586		100	100
11/3	2744.3	80.4	3	11.745		100	100
11/4	2668.8	164.8	4	5.272		100	100
11/6 and 11/7	2394.3	185.6	6	3.202		100	100
Marshall Flow (Spec Limits = 8 to 16)							
10/16 and 10/17	15.4	.346	6	21.387	1.734	98+	100
10/18	16.3	.812	4	10.222	-0.369	37+	50**
10/19	17.5	1.323	3	7.181	-1.134	5+	50**
10/20	17.0	.957	4	9.404	-1.045	15+	50**
10/21	14.5	1.966	3	3.306	0.763	72+	80
10/23	15.6	1.250	3	6.080	0.320	58+	50**
10/24	14.9	.995	4	6.935	1.106	86+	98
10/25	16.7	.651	3	13.364	-1.075	11+	50**
10/26	15.0	1.427	4	4.905	0.701	73+	80
10/27	15.7	.850	3	9.059	0.353	59+	50**
10/28 and 10/30	15.9	.173	3	45.665	0.578	66+	70
10/31 and 11/1	16.2	1.546	5	5.304	-0.129	46+	50**

TABLE 6.7 (CONTINUED)

Date	Mean Value	Standard Deviation	Sample Size	Quality Index Q_L	Quality Index Q_U	Estimated PWL	Percent Payment
Marshall Flow (Spec Limits = 8 to 16)							
11/2	15.3	1.422	3	5.134	0.492	64+	50**
11/3	15.4	.751	3	9.854	0.799	74+	80
11/4	16.1	.424	4	19.104	-0.236	42+	50**
11/6 and 11/7	17.7	.967	6	10.031	-1.758	1+	50**
Air Voids (Spec. Limit 2.0-4.0)							
10/16 and 10/17	2.3	.399	6	0.752	4.261	76+	99
10/18	2.1	.377	4	0.265	5.040	58+	80
10/19	3.7	.907	3	1.874	0.331	59+	80
10/20	2.6	.299	4	2.007	4.682	100	100
10/21	2.5	.306	3	1.634	4.902	100	100
10/23	2.5	.819	3	0.611	1.832	67+	95
10/24	3.4	.216	4	6.481	2.778	100	100
10/25	3.7	.427	3	3.981	0.703	70+	97.5
10/26	3.1	.572	4	1.923	1.573	100	100
10/27	3.0	.404	3	2.475	2.475	100	100
10/28 and 10/30	3.2	.351	3	3.419	2.279	100	100
10/31 and 11/1	2.9	.614	5	1.466	1.792	95+	100
11/2	2.8	.351	3	2.279	3.419	100	100
11/3	2.5	.058	3	8.621	25.862	100	100
11/4	2.1	.100	4	1.000	19.000	83+	100
11/6 and 11/7	2.8	.471	6	1.699	2.548	98	100

*Payment levels indicated are for the individual properties, i.e. stability, flow, or air voids.
**Remove and replace or accept at 50 percent payment.

TABLE 6.8 CALCULATIONS OF PRICE ADJUSTMENTS FOR MARSHALL PROPERTIES FOR THE SIMULATION ON THE LINDEN PROJECT

Date	Mean Value	Standard Deviation	Sample Size	Quality Index Q_L	Quality Index Q_U	Estimated PWL	Percent Payment*
Marshall Stability (Spec Limit = 1800)							
11/10	2152.8	58.8	4	6.000		100	100
11/13	2072.8	100.0	4	2.727		100	100
11/14	1950.0	71.5	4	2.098		100	100
11/15	2182.8	213.5	4	1.793		100	100
11/16	2162.8	46.9	4	7.736		100	100
11/17	2147.8	32.7	4	10.636		100	100
11/20	2111.0	255.2	4	1.215		90+	100
11/21	2246.8	110.0	4	4.062		100	100
11/22	2045.5	194.7	4	1.261		92+	100
11/24	2114.3	28.6	4	10.990		100	100
11/29	2098.5	47.3	4	6.311		100	100
11/30	2092.8	31.7	4	9.237		100	100
12/1	2103.3	50.9	4	5.959		100	100
Marshall Flow (Spec Limits = 8 to 16)							
11/10	12.5	0.35	4	12.357	10.000	100	100
11/13	12.7	0.94	4	5.000	3.511	100	100
11/14	11.3	1.41	4	2.340	3.333	100	100
11/15	12.0	0.83	4	4.819	4.819	100	100
11/16	10.4	1.53	4	1.569	3.660	100	100
11/17	11.4	1.12	4	3.036	4.107	100	100
11/20	12.8	1.61	4	2.981	1.988	100	100
11/21	10.9	0.87	4	3.333	5.862	100	100
11/22	11.7	0.85	4	4.353	5.059	100	100
11/24	11.8	1.08	4	3.519	3.889	100	100
11/29	12.1	1.02	4	4.020	3.824	100	100
11/30	12.5	1.34	4	3.358	2.612	100	100
12/1	12.2	1.61	4	2.609	2.360	100	100

TABLE 6.8 (CONTINUED)

Date	Mean Value	Standard Deviation	Sample Size	Quality Index Q_L	Quality Index Q_U	Estimated PWL	Percent Payment*
Air Voids (Spec Limit = 2.7 to 4.7)							
11/10	4.3	0.200	4	8.000	2.000	100	100
11/13	4.2	0.920	4	1.630	0.543	68+	95
11/14	4.2	0.229	4	6.550	2.183	100	100
11/15	4.0	0.441	4	2.948	1.587	100	100
11/16	4.2	0.267	4	5.618	1.873	100	100
11/17	4.0	0.159	4	8.176	4.403	100	100
11/20	3.1	1.550	4	0.258	1.032	42+	60
11/21	3.6	1.060	4	0.849	1.038	62+	90
11/22	3.3	0.607	4	0.988	2.306	82+	100
11/24	3.9	0.183	4	6.557	4.372	100	100
11/29	3.9	0.443	4	2.709	1.806	100	100
11/30	3.9	0.436	4	2.752	1.803	100	100
12/1	3.8	0.096	4	11.458	9.375	100	100

*Payment levels indicated are for the individual properties, i.e., stability, flow, or air voids.

TABLE 6.9 SUMMARY OF PRICE ADJUSTMENTS FOR THE SIMULATION ON THE ADIRONDACK - TYPE B PROJECT

Date	Daily Tonnage	Density Pay Factor*	Marshall Pay Factor**	Total Payment*** (Percent)
9/29	398	1.0	1.0	100
9/30	425	1.0	1.0	100
10/2	480	.988	0.70	69.2
10/3	957	1.0	1.0	100
10/4	481	1.0	1.0	100
10/5	698	1.0	1.0	100
10/11	822	1.0	0.95	95.0
10/12	1040	1.0	1.0	100
10/16	185	.906	0.975	88.0
10/17	204	1.0	0.975	97.5

*Values obtained from Table 6.3

**Values are the product of the pay factors for stability, flow, and air voids from Table 6.6 (e.g. for 10/2 Marshall Pay Factor = 1.0 x 0.70 x 1.0 = 0.70)

***Total Payment = Density Pay Factor x Marshall Pay Factor. This method is used for the purpose of illustration. An ultimate decision concerning the appropriateness of this method must be made by the FAA after further research.

TABLE [illegible] 1 SUMMARY OF PRICE ADJUSTMENTS FOR THE SIMULATION ON THE CHARLOTTESVILLE [illegible] PROJECT

Date	Daily Tonnage	Density Pay Factor*	Marshall Pay Factor**	Total Payment*** (Percent)
10/17	627	1.0	.975	97.5
10/18	822	1.0	.400	40
10/19	476	1.0	.400	40
10/20	829	1.0	.500	50
10/21	610	1.0	.800	80
10/23	1430	.958	.475	45.5
10/24	1226	1.0	.980	98
10/25	1120	1.0	.488	48.8
10/26	784	1.0	.800	80
10/27	311	.5	.500	25
10/28	336	.5	.700	35
10/31	159	.774	.500	38.7
11/1	785	.5	.500	25
11/2	?	.955	.500	47.8
11/3	?	.5	.800	40
11/4	1081	.5	.475	23.8
11/6	1324	.5	.500	25

*Values obtained from Table 6.4

**Values are the product of the pay factors for stability, flow, and air voids from Table 6.7

***Total Pay Factor = Density Pay Factor x Marshall Pay Factor. This method is used for the purpose of illustration. An ultimate decision concerning the appropriateness of this method must be made by the FAA after further research.

TABLE 6.11 SUMMARY OF PRICE ADJUSTMENTS FOR THE SIMULATION ON THE LINDEN PROJECT

Date	Daily Tonnage	Density Pay Factor*	Marshall Pay Factor**	Total Payment*** (Percent)
11/10	828	1.0	1.0	100
11/13	866	1.0	0.95	95
11/14	690	1.0	1.0	100
11/15	549	1.0	1.0	100
11/16	699	1.0	1.0	100
11/17	219	1.0	1.0	100
11/20	698	1.0	0.60	60
11/21	725	1.0	0.90	90
11/22	516	1.0	1.0	100
11/24	637	1.0	1.0	100
11/29	694	1.0	1.0	100
11/30	587	1.0	1.0	100
12/1	565	1.0	1.0	100

*Values obtained from Table 6.5

**Values are the product of the pay factors for stability, flow, and air voids from Table 6.8

***Total Pay Factor = Density Pay Factor x Marshall Pay Factor. This method is used for the purpose of illustration. An ultimate decision concerning the appropriateness of this method must be made by the FAA after further research.

exception of flow for the Charlottesville - ANJ project. In fact, there were no price adjustments assessed for stability. The flow results for the Charlottesville - ANJ project indicated numerous, severe price reductions. This was expected since many of the daily production means exceed the allowable upper limit of 16. The significance of these numerous price adjustments will be addressed below.

The simulation results for air voids indicated a few minor price reductions on each of the projects, but with one exception no payment level was below 80 percent. It was anticipated that air voids would not present a major problem on these projects since the projects all had above average control, as evidenced by their standard deviation values.

The total payment factors for each lot for each of the three projects are presented in Tables 6.9 through 6.11. The tables list the daily production tonnage, density price adjustment factors, Marshall price adjustment factors, and total pay factors for each day's production. The Marshall pay factor is the product of the three pay factors (stability, flow, air voids) from Tables 6.6 through 6.8. The total pay factor for each lot is the product of the density and Marshall pay factors. This method for determining the total pay factor is used only to illustrate its application. The ultimate decision regarding the applicability and use of this method can only be made by the FAA after further study.

The results of the simulation indicate that for the Adirondack - Type B and Linden projects the majority of the material would have been accepted at 100 percent payment. On the Linden project, 100 percent payment would have been made for 5984 tons out of a total tonnage of 8273, with at least 90 percent payment for 7575 tons. For the Charlottesville - ANJ

project, on the other hand, not a single lot of material would have been accepted at full price. In fact, most of the material would have been rejected and ordered replaced, or else accepted at 50 percent payment or less.

The results of such a simulation can be misleading. The results that indicate few price adjustments are probably appropriate, but the results obtained on the Charlottesville - ANJ project should be considered suspect. It can be assumed that if this project had been conducted under the proposed acceptance plan, the price adjustments early in the project would have provided an incentive for the contractor to control his process within the specification limits. Under the specifications used on the project, as long as the engineer were willing to accept material that did not meet the specifications, there would be no incentive for the contractor to conform to the specification limits. This project, which had a drier-drum asphalt plant, was included in the simulation primarily to indicate what could happen on a project which exhibited very poor control. On the basis of conversations with the FAA, it has been determined that the drier-drum process in general is under review by the FAA, and that the Charlottesville - ANJ project may not necessarily be representative of FAA projects.

Field Simulation Program

Because it is difficult to determine how a proposed acceptance plan will perform before it is tested in the field, it is recommended that the plans be simulated on construction projects in progress during the next construction season, before the plans are adopted on a full-scale basis. The simulation should be conducted on a few projects which could be monitored closely. It is important that all parties involved in the projects--FAA, owner, engineer,

and contractor--be aware of the purpose of the simulation and that they be willing to cooperate. Such a field simulation would provide the only real means for evaluating the potential operation and reasonableness of the proposed plans. It would also allow time for modifications, such as changes in acceptance or payment levels or in tolerance limits, before the plan were used for acceptance and price adjustment purposes.

POTENTIAL MODIFICATIONS

In light of the results of the simulation presented in this chapter, the FAA may wish to consider two modifications to the proposed acceptance plans. The first modification deals with the appropriateness of multiplying together the price adjustments for density and the Marshall properties. Whereas density is primarily field related, the Marshall properties are primarily batch-plant related. Because potential legal problems could result in the assessment of price adjustments when there are separate material suppliers and field contractors involved on a project, the FAA may wish to consider an approach which separates the price adjustments, for example, by dividing the production of material at the batch plant and the field placement of the material into separate bid items. This approach could be evaluated in the previously recommended field simulation during the upcoming construction season.

The other possible modification relates to the results of the simulation on the Charlottesville - ANJ project (Table 6.10). It is anticipated that the results on this project would have been different had price adjustments actually been applied early in the project. The modification which may be considered is to put some sort of minimum value on the total payment

determined for a particular lot of material. The multiplicative approach used in the simulation resulted in numerous payment factors ranging from 23.8 percent to 50 percent. The FAA might consider placing on the total payment a lower limit similar to the one on the individual properties. The lower limit on all of the properties is stated as being 50 percent payment, or the removal and replacement of the material at the contractor's expense. This option could also be placed on the total payment for the lot, with the decision being made by the project engineer.

7. SUMMARY AND RECOMMENDATIONS

This chapter summarizes the findings of a research effort to develop recommendations for the use of statistically based specifications, including price adjustments, for bituminous airport construction. For the study, data were collected on 13 airport construction projects during the 1978 construction season by the FAA Eastern Region. These data were provided to the researchers for the purpose of making an analysis and recommendations concerning proposed acceptance plans and price adjustments. It was noted that the data were not collected in accordance with a previously designed experiment; as a result, it would not be possible to determine the relative importance of the components of variability associated with the process.

On the basis of a literature review, several decisions and recommendations concerning the FAA acceptance plan were made. It was decided to use the percentage within limits (PWL) approach to determine the acceptability of the material, because this approach takes both the mean and variability of the material into account. Since no direct correlations were identified between the acceptance characteristics used by FAA and pavement life or serviceability, it was decided to base the acceptance plan on the reasonableness of its Operating Characteristics (OC) curves and Expected Payment curves.

An acceptance plan was developed for mat density. It is recommended that the acceptance plan be based on estimated PWL values, as determined by the mean and standard deviation of the sample results rather than by the range method previously used by FAA. The acceptance plan includes a continuous price adjustment schedule based upon several straight line equations that relate the estimated PWL value to the percent payment. A computer program for determining the area beneath the non-central t-distribution was

used as a convenient approximation for developing the expected payment curve for the continuous price adjustment schedule.

Acceptance plans for the Marshall properties of stability, flow and air voids were developed. For the case of Marshall stability and flow, the proposed acceptance plans used the price adjustment schedule developed by the FAA Eastern region for density. For the case of air voids, a number of different price adjustment schedules were considered. OC curves and Expected Payment curves were presented for the proposed acceptance plans for each of the Marshall properties. Discrete price adjustment schedules were used in order to simplify the calculations and facilitate application in the field since all parties involved were already familiar with the discrete density price-adjustment schedule employed during the past construction season. These plans can easily be converted into continuous price-adjustment schedules by using straight line equations in the manner employed for the proposed density acceptance plan. The operating characteristics for the case of flow and air voids were obtained by computer simulation since these properties have both upper and lower specification tolerance limits. The correlation coefficients for these properties were determined for each of the projects studied in an effort to eliminate the need for measuring all three properties for acceptance. However, no consistently high correlations were identified. Various procedures were identified for dealing with the case when the test results for more than one property indicate that a price adjustment is necessary.

Because of difficulties with the method for determining the air voids content, it was recommended that the FAA consider revising the current procedure, which may have contributed to the high standard deviation value

obtained for air voids content on the projects studied. In light of the possible change in the procedure for air voids calculation, it is recommended that air voids not be considered for price adjustments at this time. Additional data should be collected while using the procedure ultimately adopted, whether it be a continuation of the existing procedure or a new method, and a price adjustment schedule should be developed upon analysis of this additional data.

The results of the analysis of the extraction test results and the results of the theoretical hot bins gradation were presented. The pooled standard deviations for asphalt content and the various sieve sizes were compared with the quality control tolerance limits specified in the FAA Eastern Region P-401 specification. A correlation was attempted between the extraction test results and the results of the Marshall tests for each project that had results for both tests. If a strong correlation could be identified, then extraction test results might be a replacement for Marshall tests for acceptance purposes. No correlations were identified, but the results are unreliable as a consequence of the way in which the data were collected and the fact that they did not result from a designed experiment. Recommendations were made for a formal correlation program, which could be conducted on future construction projects.

The operation of the proposed acceptance plans was simulated on the test results of three of the projects from the study. The results of this simulation were presented. In order to determine how well the acceptance plans will perform, it is strongly recommended that their application be simulated on several closely monitored projects in the upcoming construction season. The results from these projects could then be evaluated, and

modifications concerning acceptance levels, price adjustments, tolerance limits, and the application of multiple price adjustments could be made before the acceptance plan is used for determining the acceptibility and price adjustments for material.

Future Research Needs

During the course of this research effort, a number of areas requiring future research were identified:

1. A research effort is needed to correlate acceptance test results with their effects on the actual field performance or life of the in-place pavement systems. Such a program would involve both laboratory testing programs and field evaluation of existing pavements. The field evaluation program could utilize the abundant data available from the statistically based specifications which have been employed for years by various state highway agencies.
2. A field simulation should be conducted in the upcoming construction season by FAA to evaluate the proposed acceptance plans. Such a simulation would help to determine the appropriateness of the plans and to identify any potential field application problems which might be associated with them.
3. Additional research should be conducted in the application of price adjustments when more than one acceptance characteristic is involved. Emphasis should be put on the legal ramifications of applying price adjustments when there are separate material producers and field constructors.

4. Statistical specifications should be extended to other FAA construction items, such as portland cement pavements, aggregate base courses, and embankment construction. Efforts similar to the one presented in this report could be made for each of the above items.
5. A formal correlation program should be implemented to identify correlations between the results of Marshall tests, asphalt content, gradation, and density in order to avoid testing all of these properties. Such a program should be a designed experiment rather than an analysis of production test results after the fact as attempted in this report.
6. An attempt should be made to correlate the density results obtained by nuclear density devices with those obtained from cores and to determine the possible differences between these methods for determining acceptance. Should a formally designed experiment determine large differences in the amounts of sampling and testing variability associated with these two methods, these differences may have to be reflected in the acceptance plans and specifications.
7. Once any differences between density measurement by cores and nuclear devices have been identified, a sample size for nuclear density measurements should be adopted on the basis of field considerations. It may then be necessary to develop tables similar to Table 3.5 for the sample size that is adopted.

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APPENDIX A

COMPUTER SIMULATION PROGRAM FOR DEVELOPING OPERATING CHARACTERISTICS CURVES

The program presented in this appendix can be used to generate via simulation the distribution of the estimated "percent within limits" (PWL) of a product, and to develop the OC curves for an acceptance plan that has both upper and lower tolerance limits. By entering a very large (or small) fictitious upper (or lower) limit that will never be exceeded, the program can also be used for one-sided specification limits. The program simulates the drawing of a large number of samples in the field.

For the OC curves developed in this study, the program was used to simulate the drawing of 10,000 samples of a given sample size. For each of the 10,000 samples, the program calculates the mean, standard deviation, and quality index and determines the estimated PWL value for the sample. The program's tally of the estimated PWL values for all of the samples drawn can be used to determine the distribution of the estimated PWL values for the particular specification limits, sample size, and population parameters used in the simulation.

The following variables are necessary input to the program:

N	= Sample size used in estimating PWL
NM	= Number of populations studied
AM(I), I=1, ... NM	= Mean of each of the NM populations studied
NIT	= Number of repetitions used in the simulation
BL	= Lower tolerance limit
UL	= Upper tolerance limit
SIG	= Standard deviation of the NM populations studied.

Additional required input data are the Quality Index values for estimating PWL, which appear on lines 9600 through 9850 for the program shown in Exhibit A-1.

Sample Program

To help illustrate the use of the simulation program for the development of OC curves, a sample program is included in Exhibit A-1 and a portion of the output from this program is presented in Exhibit A-2. The program presented in Exhibit A-1 was used to determine the OC curves shown in Figure 4.13. For a full understanding of the program presented in Exhibit A-1, it may be helpful to go through the program from start to finish.

The simulation in Exhibit A-1 is for air voids content, a fact noted on line 450 of Exhibit A-1 and shown on line 13,000 of the printout in Exhibit A-2. The necessary information for the simulation is input to the program by the READ statements on lines 500 and 600 in Exhibit A-1. Line 500 causes the values from the first data card (Line 9550) to be read for N, NM, NIT, AM(I), BL, UL and SIG (defined above). Line 9550 shows that for this simulation the following are used:

Sample size (N) = 4

Populations being studied (NM) = 6

Number of repetitions (NIT) = 10,000

Means of populations being studied (AM(I), I=1, ... 6) = 3.7, 3.9, 4.1, 4.3, 4.5, and 4.7

Lower tolerance limit (BL) = 2.7

Upper tolerance limit (UL) = 4.7

Standard deviation of the populations being studied (SIG) = 0.75.

Line 600 causes the quality index values for a sample size of four to be read from the next data cards. These values, which appear on lines 9600 through 9850 of Exhibit A-1, correspond to the quality index values (from Table 3.5) for PWL estimates of 99 percent down to 50 percent.

Beginning on line 1150 is a DO loop which draws the sample and performs the necessary operations to determine the estimated PWL value for the sample. These operations are repeated until the designated number of repetitions (NIT = 10,000 in this example) have been completed.

The call to subroutine PRAND (line 1200) causes random numbers to be read from a tape containing one million uniformly distributed random numbers with a mean of zero and variance of one. The call to subroutine RNORM then converts the numbers read from the tape into numbers which are normally distributed with a mean of zero and a variance of one. After the program converts these numbers to numbers with a standard deviation equal to that of the populations being simulated (line 1350), the program converts the latter numbers to ones having the mean of the population being simulated and calculates the upper and lower quality index values (Q_U and Q_L) for the sample (lines 2050 and 2100). The final step is the determination of the estimated PWL value for the sample and the recording of this value in the appropriate category, to be printed at the completion of the simulation (lines 2150 through 3750).

An example of a portion of the output from the program is shown in Exhibit A-2. The output provides a tabulation of the number of PWL estimates from the total number of repetitions that are equal to or lower than a given PWL value. For example, for the sample output in Exhibit A-2, there are 4344 estimates less than or equal to a PWL of 79.9 percent. Thus, if an

estimate of at least 80.0 percent is required for 100 percent payment, the probability of receiving full payment is 10,000 minus 4344, divided by 10,000, which equals 0.5656, or 56.56 percent.

EXHIBIT A.1 COMPUTER SIMULATION PROGRAM

```
/*TAPE RAND1
// EXEC FGCG
//SOURCE.INPUT DD *
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4 U(600)
      DIMENSION X(101),MF(6,500),PWL(101),AM(6),XA(6),XA2(10)
      DATA MF,XA,XA2/3000*0,16*0.0D0/
      PRINT 1111
 1111 FORMAT ('OTHIS SIMULATION IS FOR AIR VOIDS                ')
      READ 15,N,NM,NIT,(AM(I),I=1,NM),BL,UL,SIG
   15 FORMAT (2I2,I6,10F7.2)
      READ 18,(X(I),I=1,51)
   18 FORMAT (10F7.0)
      DO 19 I=1,51
   19 PWL(101-I) = X(I)
      CALL BASET(00001)
      PRINT 1122
 1122 FORMAT ('O THIS PROGRAM IN FILE FAASIM4  ')
      PRINT 16
      PRINT 15,N,NM,NIT,(AM(I),I=1,NM),BL,UL,SIG
   16 FORMAT('ON NM  NIT  MEANS                                      LIM
     1ITS        SIG')
      DO 1000 IIT=1,NIT
      CALL PRAND(U,5*N)
      CALL RNORM(X,U,N)
      DO 24 IP=1,N
      X(IP) = X(IP)*SIG
   24 CONTINUE
      XB = 0.0D0
      DO 26 IP=1,N
      XB = XB + X(IP)
   26 CONTINUE
      XB = XB/N
      SS = 0.0D0
      DO 28 IP=1,N
      SS = SS + (X(IP)-XB)**2
   28 CONTINUE
      SS = SS/(N-1)
      S = DSQRT(SS)
      DO 50 J=1,NM
      QL = (XB + AM(J) - BL)/S
      QU = (UL - XB - AM(J))/S
      IF(QL.LT.PWL(100)) GO TO 59
      PL = 0.0D0
      GO TO 95
   59 DO 51 I=1,51
      JJ = 100- I
      AZZZ = PWL(JJ)
      IF(QL.GT.AZZZ) GO TO 61
   51 CONTINUE
```

```
      PL = 51.0D0
      PU = 0.0D0
      GO TO 195
   61 F = (QL - PWL(JJ))/(PWL(JJ+1) - PWL(JJ))
      PL = 100.0D0 - JJ -F
   95 IF(QU.LT.PWL(100)) GO TO 62
      PU = 0.0D0
      GO TO 195
   62 DO 63 I=1,51
      JJ = 100 -I
      AZZZ = PWL(JJ)
      IF(QU.GT.AZZZ) GO TO 64
   63 CONTINUE
      PU = 51.0D0
      GO TO 195
   64 F = (QU - PWL(JJ))/(PWL(JJ+1) - PWL(JJ))
      PU = 100.0D0 - JJ - F
  195 PD = (100.0D0 - PU - PL) * 10.0D0 - 498.0D0
      XA(J) = XA(J) + 100.0D0 - PU - PL
      XA2(J) = XA2(J) + (100.0D0 - PU - PL)**2
      IPD = PD
      IF(IPD.LT.1)IPD=1
      IF(IPD.GT.500)IPD=500
   50 MF(J,IPD) = MF(J,IPD) + 1
 1000 CONTINUE
      DO 75 I=1,10
   75 X(I) = (I-1)*0.1D0
   76 FORMAT('       ',10F6.1)
      DO 72 J=1,NM
      DO 73 I=2,500
   73 MF(J,I) = MF(J,I) + MF(J,I-1)
      PRINT 74,AM(J)
   74 FORMAT(//,' DIST OF VALUES FOR MEAN=',F8.2)
      PRINT 76,(X(I),I=1,10)
      DO 77 I=1,50
      JJ = I + 49
      JL = (I-1)*10 + 1
      JU = JL + 9
      IF(MF(J,JL).EQ.MF(J,JU)) GO TO 77
      PRINT 78,JJ,(MF(J,IT),IT=JL,JU)
   78 FORMAT (11I6)
   77 CONTINUE
      XXX = XA(J)
      XA(J) = XA(J)/NIT
      SS22 = (XA2(J) - XA(J) * XXX)/NIT
      SS22 = DSQRT(SS22)
      PRINT 87,XA(J),SS22
   72 CONTINUE
   87 FORMAT (' AVERAGE VALUE = ',F12.3,'STANDARD DEVIATION =',F12.3)
      STOP
      END
```

```
      SUBROUTINE PRAND (U,NO)
C     SUBROUTINE PRAND AS FOLLOWS MAY BE USED IN PLACE OF THE LIBRARY
C     SUBROUTINE PRAND TO RETRIEVE UP TO ONE MILLION UNIFORM(0,1)
C     RANDOM SINGLE PRECISION REAL NUMBERS DERIVED FROM THE RAND TAPE.
C
C     TO CONTINUE FROM JOB TO JOB:
C     NOTE THAT THE CALL TO BASAVE RETURNS THE NUMBER OF NUMBERS
C     ADVANCED ON THE TAPE UP TO THE POINT OF INVOKATION.  BASET CAN
C     THEN BE CALLED IN A SUBSEQUENT RUN WITH THIS NUMBER SO THAT THE
C     REMAINING UNUSED NUMBERS ON THE TAPE ARE THEN RETURNED VIA
C     SUBSEQUENT CALLS TO PRAND.  BASET SHOULD NOT BE CALLED AFTER A
C     CALL TO PRAND IN THE SAME RUN AS THIS CAUSES THE TAPE TO BE
C     REWOUND AT THE PROBLEM PROGRAM'S EXPENSE.
C
C     H. D. KNOBLE  -  JANUARY, 1972  -  PSU COMPUTATION CENTER.
      DIMENSION X(400), U(NO)
      DATA K/400/, NREC/-1/, LRECL/400/, IUNIT/92/
C
      NUM=NO
      M=0
  100 IF (K.EQ.LRECL) GO TO 400
  200 L=MINO(LRECL-K,NUM)
      NUM=NUM-L
      DO 300  J=1,L
      M=M+1
  300 U(M)=X(K+J)
      K=K+L
      IF (NUM.EQ.0) RETURN
      GO TO 100
  400 READ (IUNIT,END=500) X
      NREC=NREC+1
      K=0
      GO TO 200
C        IF AN END OF FILE IS ENCOUNTERED A STOP IS EFFECTED.  THIS
C        COULD BE CHANGED TO A REWIND IUNIT TO ENABLE PROCESSING TO
C        CONTINUE.
  500 WRITE (6,600) NREC,K,J
  600 FORMAT ('0$$$$PRAND: END OF FILE ENCOUNTERED ON RAND TAPE,',/' ','
     1 NREC,K,J=',3I11)
C     TRACE GIVES A TRACEBACK; IN WATFIV CHANGE TO   CALL EXIT.
C     CALL TRACE
      STOP 8
C-----------------------------------ENTRY BASAVE
C        BASAVE RETURNS THE NUMBER OF NUMBERS ADVANCED ON THE TAPE.
      ENTRY BASAVE (N)
      N=NREC*LRECL+K
      WRITE (6,700) N
  700 FORMAT (' $$$$BASAVE: NUMBERS USED UP TO THIS POINT =',I11,//)
      RETURN
```

AD-A080 430 PENNSYLVANIA TRANSPORTATION INST UNIVERSITY PARK F/G 1/5
ACCEPTANCE CRITERIA FOR BITUMINOUS SURFACE COURSE ON CIVIL AIRP--ETC(U)
OCT 79 J L BURATI, J H WILLENBROCK DOT-FA78WA-4185
UNCLASSIFIED PTI-7915 FAA-RD-79-89 NL

3 OF 3
AD A080430

END
DATE FILMED
3-80
DDI

EXHIBIT A.1 (CONT.)

```
C---------------------------------ENTRY BASET
C         BASET POSITIONS THE TAPE TO THE (I+1)TH NUMBER.
      ENTRY BASET (I)
      REWIND IUNIT
      NREC=I/LRECL
      K=MOD(I,LRECL)
      IF(I.EQ.0) RETURN
      IF (NREC.EQ.0) GO TO 900
      DO 800  J=1,NREC
  800 READ (IUNIT,END=500)
  900 READ (IUNIT,END=500) X
      RETURN
      END
      SUBROUTINE RNORM(X,U,N)
      DIMENSION U(600)
      REAL*8 X(50)
       NB2=N/2
      ITS=0
      DO 1 I=1,NB2
20    ITS=ITS+1
      IS=2*ITS-1
      IS1=IS+1
      U1=U(IS)
      U2=U(IS1)
      V1=2*U1-1
      V2=2*U2-1
      ES=V1**2+V2**2
      IF(ES.GE.1) GO TO 20
      ARG=-2*ALOG(ES)/ES
      FACT=SQRT(ARG)
      ID=2*I-1
      ID1=ID+1
      X(ID)=V1*FACT
      X(ID1)=V2*FACT
1     CONTINUE
      RETURN
      END
//DATA.FT92F001 DD UNIT=2400,VOL=SER=RAND1,DSN=UNIFORM,
// DCB=(RECFM=VBS,LRECL=1604,BLKSIZE=3212),LABEL=(1,,,IN)
//DATA.INPUT DD *
 4 6 10000     3.7     3.9     4.1     4.3     4.5     4.7     2.7     4.7   0.75
 1.5000 1.4700 1.4400 1.4100 1.3800 1.3500 1.3200 1.2900 1.2600 1.2300
 1.2000 1.1700 1.1400 1.1100 1.0800 1.0500 1.0200 0.9900 0.9600 0.9300
 0.9000 0.8700 0.8400 0.8100 0.7800 0.7500 0.7200 0.6900 0.6600 0.6300
 0.6000 0.5700 0.5400 0.5100 0.4800 0.4500 0.4200 0.3900 0.3600 0.3300
 0.3000 0.2700 0.2400 0.2100 0.1800 0.1500 0.1200 0.0090 0.0060 0.0030
 0.0000
/*
```

EXHIBIT A.2 A PORTION OF THE PROGRAM OUTPUT

```
13000 THIS SIMULATION IS FOR AIR VOIDS
13050  THIS PROGRAM IN FILE FAASIM4
13100 N NN  NIT   MEANS                                                   LIMITS        SIG
13150 4 6 10000    3.70    3.90    4.10    4.30    4.50    4.70    2.70    4.70    0.75
13200
13250
13300 DIST OF VALUES FOR MEAN=    3.70
```

13350		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
13400	50	330	331	332	339	341	347	351	356	361	365
13450	51	368	372	374	380	387	391	397	401	408	413
13500	52	419	426	434	439	441	450	451	457	464	471
13550	53	476	487	499	507	515	529	537	546	558	572
13600	54	584	591	597	603	611	620	628	636	643	652
13650	55	660	667	677	686	693	703	715	722	733	741
13700	56	751	762	771	780	794	803	814	826	833	842
13750	57	850	860	872	880	885	897	906	914	925	935
13800	58	944	953	968	981	985	991	1003	1012	1024	1042
13850	59	1051	1056	1064	1071	1084	1097	1118	1128	1140	1154
13900	60	1169	1181	1194	1212	1227	1243	1255	1267	1281	1287
13950	61	1295	[illegible]	1326	1340	1353	1370	1384	1395	1403	1417
14000	62	1437	1447	1459	1469	1480	1496	1507	1525	1539	1553
14050	63	1571	1583	1595	1612	1631	1653	1658	1666	1684	1704
14100	64	1724	1738	1751	1761	1771	1786	1801	1812	1825	1842
14150	65	1857	1868	1886	1905	1913	1925	1937	1950	1960	1972
14200	66	1987	2005	2023	2041	2063	2082	2092	2108	2116	2133
14250	67	2145	2161	2179	2196	2213	2228	2248	2268	2280	2295
14300	68	2306	2321	2352	2367	2379	2390	2413	2427	2445	2469
14350	69	2489	2508	2516	2536	2549	2569	2581	2595	2607	2620
14400	70	2633	2649	2663	2680	2699	2713	2726	2743	2760	2781
14450	71	2801	2820	2836	2853	2873	2893	2910	2927	2938	2950
14500	72	2967	2988	3005	3027	3041	3061	3083	3098	3111	3123
14550	73	3134	3148	3169	3186	3207	3227	3246	3266	3288	3304
14600	74	3323	3341	3358	3374	3397	3415	3440	3453	3470	3487
14650	75	3508	3527	3545	3559	3574	3592	3609	3622	3636	3658
14700	76	3674	3692	3708	3728	3742	3762	3772	3784	3801	3820
14750	77	3834	3849	3872	3888	3900	3914	3933	3950	3970	3990
14800	78	4012	4026	4035	4054	4067	4080	4109	4130	4153	4165
14850	79	4178	4201	4216	4237	4257	4281	4297	4310	4324	4344
14900	80	4356	4368	4387	4410	4427	4448	4470	4489	4507	4522
14950	81	4543	4560	4585	4603	4619	4628	4647	4659	4683	4701
15000	82	4722	4738	4755	4780	4797	4817	4835	4850	4864	4880
15050	83	4891	4909	4917	4933	4953	4969	4990	5011	5032	5044
15100	84	5057	5087	5101	5114	5136	5152	5170	5186	5198	5221
15150	85	5242	5257	5275	5290	5311	5324	5342	5363	5384	5395
15200	86	5409	5432	5446	5467	5483	5492	5508	5520	5535	5544
15250	87	5557	5580	5601	5615	5629	5644	5658	5675	5690	5709
15300	88	5722	5742	5753	5769	5784	5801	5821	5837	5856	5866

EXHIBIT A.2 (CONT.)

15350	89	5876	5888	5897	5916	5933	5951	5964	5977	5991	6006
15400	90	6018	6031	6047	6068	6078	6091	6109	6122	6136	6151
15450	91	6166	6182	6200	6210	6222	6232	6248	6263	6275	6291
15500	92	6304	6322	6338	6352	6368	6379	6397	6409	6425	6438
15550	93	6455	6463	6472	6486	6500	6510	6524	6539	6550	6558
15600	94	6569	6586	6597	6609	6628	6648	6654	6667	6683	6697
15650	95	6710	6717	6726	6741	6757	6771	6780	6800	6811	6823
15700	96	6843	6854	6868	6885	6895	6913	6924	6936	6949	6962
15750	97	6975	6989	7002	7024	7035	7049	7058	7079	7091	7100
15800	98	7114	7128	7138	7146	7156	7164	7170	7178	7189	7200
15850	99	7212	7223	7235	7247	7258	7275	7288	7297	7313	10000

15900 AVERAGE VALUE = 81.899STANDARD DEVIATION = 16.283
15950
16000